Universidade de Aveiro Departamento de Biologia
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Rosa de Fátima Lopes de Freitas

Utilização de métodos acústicos na caracterização remota de biótopos bentónicos

Benthic biotopes remote sensing using single beam acoustics

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Biologia, realizada sob a orientação científica da Professora Doutora Ana Rodrigues, Professora Auxiliar do Departamento de Biologia da Universidade de Aveiro, e do Professor Doutor Victor Quintino, Professor Auxiliar do Departamento de Biologia da Universidade de Aveiro.

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Dedico este trabalho à minha família pelo incansável apoio.

o júri

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palavras-chave

Caracterização acústica, QTC VIEW, biótopos bentónicos, substratos móveis.

resumo

O estudo de habitats bentónicos de substratos móveis tem sido tradicionalmente baseado na recolha de amostras de sedimentos e posterior análise de descritores fisico-químicos e biológicos.

A informação obtida, nomeadamente, relativa a características dos sedimentos superficiais e das comunidades de macrofauna bentónica, embora necessária para a caracterização de habitats, recorre a metodologias de amostragem e de análise laboratorial que apresentam grandes limitações na cobertura de áreas extensas.

Recentemente desenvolvidos, métodos acústicos que recorrem à análise e classificação de ecos, vieram permitir a cobertura e mapeamento detalhado, da diversidade acústica de áreas extensas, sem recorrer à colheita de amostras de sedimentos. Contudo, estes métodos não fornecem informação sobre as características físicas e biológicas dos fundos.

Nesta dissertação são apresentados os resultados obtidos da combinação de técnicas acústicas e tradicionais na identificação e mapeamento de habitats bentónicos em vários locais da costa portuguesa.

Na amostragem acústica foi utilizado o sistema QTC VIEW^{TM}, ligado a uma eco-sonda de feixe simples com frequência de 50 kHz. Para a amostragem tradicional recorreu-se à colheita de sedimentos com draga.

Os estudos foram efectuados em locais com profundidades de amostragem muito variáveis (entre os 5 e 200 metros), caracterizados por uma grande diversidade de tipos de sedimentos e/ou comunidades de macrofauna bentónica, cobrindo uma grande diversidade de habitats de substrato móvel.

A partir dos resultados obtidos, constatou-se grande concordância entre a diversidade acústica e os gradientes bio-sedimentares, concluindo-se que o sistema acústico QTC VIEW apresenta um elevado potencial na identificação remota de habitats bentónicos, embora necessite de validação através de amostras convencionais para a interpretação das várias classes acústicas.

keywords Acoustic seabed classification, QTC VIEW, benthic biotopes, sediments.

abstract

The traditional way of identifying and mapping the distribution of sublittoral soft sediments and associated benthic communities involves taking grab samples and analysing sediment and biological descriptors. In order to ensure a detailed spatial average, this type of approach is extremely time consuming. Nevertheless, traditional sampling techniques present the advantage of offering the possibility to physically access the sediment and the benthic specimens.

The use of acoustic techniques to monitor or characterise benthic biotopes has seen numerous recent applications. These techniques are based on processing signals from single-beam echo sounders that, after calibration, produce acoustic diversity maps of the surveyed areas. However, they do not give direct information on sedimentary or biological characteristics of the sea bottom.

This thesis presents the results obtained from a combined approach using acoustic and traditional sampling techniques for the identification and mapping of sublittoral soft bottom benthic habitats. The studies were conducted in areas characterised by a large range of survey depth (5 to 200 meters) and by a high variety of sediment and/or benthic communities, covering a high diversity of soft bottoms benthic biotopes.

The acoustic survey was done with the ground discrimination system QTC VIEW^{TM}, connected to a 50 kHz single-beam echo sounder. Ground-truth of the surveyed areas included sediment and biological descriptors.

The results obtained show good agreement between the acoustic and the biossedimentary patterns and it was possible to conclude that the acoustic system QTC VIEW presents a high potential for the remote assessment of benthic biotopes, although, requiring the validation of the acoustic diversity through ground-truth samples.

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CHAPTER 1 - INTRODUCTION

1. Introduction

1.1 Acoustic systems overview

Historically, the studies concerning soft bottom benthic communities and habitats have essentially relied on the collection and analysis of sediment and biological samples. A variety of sampling devices may be used (grabs, cores, dredges, etc) but they all present the disadvantage of disturbing the structural integrity of the sediment habitat, which may result in the loss of important ecological information (Guigné et al., 1993). This approach may also be very time consuming if a detailed spatial grid is used to cover large areas. Apart from such limitations, this traditional sampling procedure is essential in studies concerning the identification and abundance of benthic species and their relation with sediment characteristics, since they offer the possibility to physically access the sediment and the benthic specimens (among others, Sanders and Hessler, 1969).

Recently, with the perspective of diminishing the limitations of the traditional sampling procedures in biological studies, acoustic techniques have been used as a complement to the conventional survey methods. The acoustic systems used in such studies, namely single-beam echo sounders, were not created for that purpose. In fact, the first acoustic system developed, a sonar type listening device, was created in 1906, as a way of detecting icebergs. The interest in sonar systems increased during World War I with the need to detect submarines. The first sonar systems were passive listening devices; in other words, they were able to listen to sounds from underwater objects but were unable to sent out signals. By 1918, both Britain and the U.S. had built active systems that were able to send out signals and receive them back. In 1919, Reginald Fessenden, developed an acoustic system, the fathometer, with the ability to measure the water depth, from which derive today echo sounders (http://inventors.about.com). The depth of a certain area was calculated by knowing the speed of the sound wave through the water; i. e. by utilizing the speed of the sound wave through the water and the time between the emitted pulse and the returning echo, the depth could be calculated.

Between the two world wars, and accompanying the development of echo sounders, several studies were done concerning the improvement of equipments for the study of the seafloor. The results of such studies revealed that sound transmission in the sea depended crucially on how the temperature and salinity of the seawater varied with depth.

At the beginning of the World War II, in 1939, the scientific understanding of sound behaviour in the sea and its application to sonar systems for anti-submarine warfare advanced and a major effort was done for the development of underwater acoustic systems. The American word SONAR was used for the first time in World War II, as an acronym for **So**und, **Na**vigation and **R**anging. However, the British used the acronym ASDIC instead, which stands for **A**nti-**S**ubmarine **D**etection **I**nvestigation **C**ommittee (http://www.wikipedia.org).

During World War II, in order to promote a safe landing of the army forces in Europe, there was the need to know, in detail, the continental shelf and the water dynamics. Consequently, new acoustic technologies were developed and important studies were carried out. It was during this period that the Side Scan Sonar was developed and its application brought new insights on the underwater topography and structures (Brown et al., 2002).

After World War II, and with the beginning of the Cold War, and accompanying the development of computers, new acoustic systems were invented such as the English system GLORIA (**G**eological **Lo**ng **R**ange **I**nclined **A**sdic). New acoustic strategies, such as seismic studies, started being used to characterise the sediments under the surface of the seabed (Bearman, 1992; Brown et al., 2002). Since 1990, the improvement on acoustic technologies brought new opportunities to explore and describe the marine environment. The most useful, highly developed and versatile systems and, consequently, the most commonly applied techniques, include Side Scan Sonar, that provides wide-area, high-resolution images of the seafloor, at all depths (Flemming et al., 1982; Fish and Carr, 1990; Morang et al., 1997; Service and Magorrian, 1997; Hughes Clarke, 1998; Bornhold et al., 1999; Brown et al., 2002); multi-beam echo sounders, used to acquire high resolution topographical images of the seabed (Morang et al., 1997); single beam echo sounders used for fish finding and to detect water depth (Flemming et al., 1982; Lurton and Pouliquen, 1992); and sub-bottom profiling systems, applied to identify and measure various sediment layers that exist below the sediment/water interface (Flemming et al., 1982; Morang et al., 1997; Smith et al., 2001; Harris and Beaman, 2003). The main working method of all these acoustic techniques is based on single or multiple transducers, which send acoustic signals into the seafloor and measure the energy of the reflected pulses. The seabed characterisation is therefore obtained through the analysis of the received reflected signals (Fish and Carr, 1990).

Due to the strong relationship between the characteristics of the seafloor and the returned acoustic pulse, the acoustic technologies were initially used to study the physical properties of the seabed, namely in geological works. Nowadays, the acoustic techniques are been applied more and more in biological studies, including the remote characterisation of marine benthic habitats (e.g. Freeman and Rogers, 2003; Freitas et al., 2003a; Hewitt et al., 2004; Foster-Smith et al., 2004; Freeman et al., 2004; Riegl and Purkis, 2005; Hutin et al., 2005).

Side Scan Sonar systems can generate an almost photo-realistic picture of the seabed, providing an easy recognition of the geological and sedimentological features of the surveyed area. Side Scan systems operating at lower frequency (around 100 kHz) provide wide swath coverage and are used to create mosaics of the entire survey area. Higher frequency systems (300 kHz) can provide higher resolution images and reveal detailed information of distinct objects or features on the seafloor. These systems have shorter ranges and are generally used to image a particular feature or area of interest (Flemming et al., 1982; Fish and Carr, 1990; Morang et al., 1997; Kenny et al., 2003). It has been demonstrated that the Side Scan Sonar provides information on sediment texture, topography and bedforms. The Side Scan Sonar backscatter (i.e. the returned acoustic signal) responds to the physical properties of the seafloor: dense objects such as rocks or coarse sand reflect stronger signals while soft features such as mud or fine sediments absorb sonar energy and produce lighter acoustic returns (Flemming et al., 1982; Fish and Carr, 1990; Morang et al., 1997; Kenny et al., 2003). In this way, Side Scan systems can identify different types of seafloor, such as mud, sand, rippled sand, rock outcrops and canyons (Fish and Carr, 1990; Limonov et al., 1997; Morang et al., 1997; Service and Magorrian, 1997; Brown et al., 2002; Kenny et al., 2003; Humborstad et al., 2004; Collier and Brown, 2005). Jointly with other methodologies, the Side Scan Sonar has been recently used for the mapping of marine benthic communities (Smith et al., 2001; Hewitt et al., 2004).

Multi and single-beam echo sounders are normally used to study the seafloor morphology and to locate bottom features such as sediment ridges, bedrock outcrops, fish groups, sunken ships or underwater cables (Rudstam et al., 1999; Beaman and Harris, 2003; Somoza et al., 2003). Although not so frequently, echo sounders have also been used for seabed habitats mapping and assessment (Weaver et al., 1997; Kenny et al., 2003). While single-beam sounders collect discrete data points along survey track lines, multi-beam sounders collect high-resolution bathymetry data throughout the survey area providing a larger bottom coverage than single-beam systems. Single-beam depth sounders have several advantages over multi-beam, since they are commonly available at a relatively low cost and portable units can be easily deployed on small boats. In addition single-beam sounders have also been coupled with the newly developed acoustic ground discrimination systems, which give information on seabed composition (among others, Freitas et al., 2003a, 2003b). Multi-beam echo sounders are far less portable than single-beam and, for this reason, they are typically mounted semi-permanently on designated vessels.

Sub-bottom profiling systems provide information about the sediment layers underlying the bottom surface. No other acoustic technique provides this type of information and only physical sampling, using cores, will allow the characterization of subsurface structures. However, the sub-bottom profiling systems do not disturb the structural integrity of the sediment, which is an advantage when compared with other sampling techniques. Nevertheless, these systems have been normally used in geological surveys concerning the characterisation of sediment layers, the detection and measuring of the thickness of dredged material deposits, the identification of hard substrate that has been covered by sedimentation and the identification of buried objects (such as cables and pipelines) (Smith et al., 2001; Harris and Beaman, 2003; Smith et al., 2003). These acoustic systems are limited by a narrow swath width, so continuous coverage of the seafloor is time-consuming and expensive to obtain. As with other single-beam acoustic methods, the area ensonified by the acoustic signal (known as the footprint) is relatively small and dependent on depth.

Recent advances in acoustic technologies brought new opportunities to explore and analyse the acoustic information obtained from marine environments. The traditional interpretation of grey scale graphic records obtained by echo sounders are now replaced by the analysis of the acoustic signals and the generation of values representing the acoustic response from an integration of seabed returned echoes. Therefore, the newly developed instruments, acoustic ground discrimination systems, such as RoxAnn™ and QTC VIEW™, are based on single beam echo sounders and are designed to detect different seabed types according to their reflectance properties (among others, Chivers et al., 1990; Magorrian et al., 1995; Collins, 1996; Collins et al., 1996; Greenstreet et al., 1997; Hamilton et al., 1999; Smith et al., 2001; Anderson et al., 2002; Ellingsen et al., 2002; Freitas et al., 2003a; 2003b; Humborstad et al., 2004; Collier and Brown, 2005).

This new approach on acoustic seafloor habitat characterization requires ground-truth verification that can be done either through physical sampling of the bottom, using sediment cores or grabs, or through visual observations by divers or underwater cameras. All types of substrate found must be verified to interpret the data accurately and link the acoustic signatures to the seabed classification scheme.

Acoustic ground discrimination systems have been used in a variety of benthic habitat assessment studies and it has been shown that these systems are able to distinguish between sand, mud, rocks, shells, and algae found on the seafloor (among others, Anderson et al., 2002; Ellingsen et al., 2002; Freitas et al., 2003a; 2003b).

There are some advantages of using an acoustic seafloor classification system, such as the fact that they are commonly available at relatively low cost, they are portable (so they can be deployed on different size boats or research vessels), and they have minimal power requirements. Also, they are capable of collecting data almost continuously along the survey lines, thus presenting a much larger spatial coverage when compared to grabs or cores point sampling. As principal disadvantages, these systems present a narrow swath width making it impossible to cover 100% of the survey area, and their acoustic footprint is relatively small and dependent on depth. Additionally, in order to interpret the acoustic diversity, these systems present dependency on field calibration, or ground-truth, through physical sampling, video, or imagery collection. However, once the calibration is done this type of equipment can be used in the same or different survey areas and the acoustic information acquired can be compared with the previously calibrated one (Collins, 1999; Kenny et al., 2003).

1.2 Acoustic ground discrimination systems, RoxAnn and QTC VIEW

Acoustic ground discrimination systems have been recently used in studies concerning marine benthic habitats and several works have shown their ability for seafloor physical characterisation through the acoustic seabed classification, based in the shape feature of the returned acoustic signal.

The most common acoustic ground discrimination systems are RoxAnn^{TM} and QTC VIEW^{TM}. The seabed characterisation performed by these acoustic systems is based on the same fundaments but the classification procedure differs.

RoxAnn^{TM}, developed in the UK in the 1980s, was the first commercial acoustic ground discrimination system. The RoxAnn^{TM} classification is based on the analysis of the energy contained in the first and second returns of the echoes (Chivers et al., 1990). The first return echo is a direct reflection from the seabed to the transducer and the second return corresponds to the bounce of the original sound pulse reflecting again on the sea surface and the seabed for the second time (Chivers et al., 1990). This acoustic system uses the tail of the first echo and the full extent of the second echo to produce two values, known as E1 and E2, which will constitute the feature set used for classification. The index E1 gives an estimation of the roughness of the sediment whilst E2 indicates the hardness of the seafloor (Chivers et al., 1990; Magorrian et al., 1995; Collier and Brown, 2005). The combination of these two factors with ground-truth calibration can provide the characterisation of the seabed ensonified and allows the identification of different sediment types from fine mud with very high silt and clay content to gravel and also their associated benthic communities (Magorrian et al., 1995; Greenstreet et al., 1997; Pinn and Robertson, 1998; Hamilton et a., 1999; Cholwek et al., 2000; Kloser et al., 2001; Smith et al., 2001).

More recent advances in acoustic ground discrimination technology have resulted in the development of the Canadian system QTC VIEW^{TM}, the acoustic system used in the studies that compose this thesis. This acoustic system operates in a very different way from RoxAnn^{TM}. In this case, the transducer acquires the returned pulse and analyses, using a series of algorithms, the shape and energy characteristics only of the first incoming echo (Collins et al., 1996). The result is a digital description of the echo consisting in 166 feature variables (Collins and Lacroix, 1997). This data set is reduced using multivariate statistics, Principal Component Analysis (PCA), and displayed on a three-dimensional plot (Q-space) where each echo is represented by three values (Q1, Q2 and Q3) corresponding to the first three principal components (Collins and McConnaughey, 1998). Echoes from similar seabed types will have similar Q-values and, consequently, when plotted against each other, will form a cluster. Using post-processing software, each cluster is mathematically defined and assigned to a class name.

Acoustic surveys using the QTC VIEW^{TM} system may be classified into two main types, depending on the target application and the available ground-truth information: supervised and unsupervised methods (Collins et al., 1996; Collins and Lacroix, 1997). In the supervised mode a series of echoes are collected from seabeds with known characteristics. Data from sites composed of different sediment types will correspond to different acoustic classes. Ground-truthing normally takes place during calibration to verify the seabed type (Collins et al., 1996). Supervised classification usually occurs when real-time mapping is important and could be applied both in studies where there is no prior knowledge of the survey area and in studies where the selection of the calibrated sites are based on preliminary interpretation of the seafloor diversity. Collins and Galloway (1998), Hamilton et al. (1999), Anderson et al. (2002), and Ellingsen et al. (2002) present studies using the supervised approach for seabed classification. The unsupervised classification is accomplished by post-processing when a series of automated statistical techniques are used to determine the extent of acoustic variability of the surveyed seabed. For this analysis a post-processing software is used and the acquired acoustic information is classified into different acoustic classes (Collins et al., 1996). Each class is then related to pre-existing ground-truth data or used to define future ground-truth sampling sites. As in works done by Morrison et al. (2001), Freeman and Rogers (2003), Hewitt et al. (2004) the unsupervised mode was used in all the studies presented in this thesis.

Several works have demonstrated that the information acquired by these acoustic systems it is not only influenced by the seafloor characteristics but that the characteristics of the acoustic signals sent into the water column also influence the information acquired from the seabed (among others, Morang et al., 1997). These characteristics are dependent on the sounder/transducer configuration parameters such as frequency, pulse duration, transmit power, ping rate and transducer beam width. The area ensonified by the echo sounder (i.e. the footprint) is approximately circular but this area depends on the beam angle (angle of the sound cone) and on the depth of the seafloor.

Concerning the echo sounder frequency, Collins and Rhynas (1998), using the QTC VIEW system, demonstrated that lower echo sounder frequencies (10 to 100 kHz) exhibit small signal losses in the water. Thus, these frequencies transmit more energy into the seabed causing the signal to penetrate deeper into the seafloor (tens of centimetres) and carry more information back to the transducer. In this case, because more volume of sediment has been ensonified, a greater amount of substrate information is included in the returning signal. Low frequency transducers generally have larger beam widths (15º-30º). Frequencies above 100 kHz suffer more attenuation in the water and therefore do not transmit as much energy to the seabed resulting in reduced penetration (few centimetres). In this case, the footprint is usually smaller resulting in less substrate information and thereby increasing seabed detailed discrimination. Thus, these frequencies are used to detect smaller differences in seabed such as smooth differences on sediment types. High frequency transducers have typically smaller beam widths (10º-20º).

The characteristics of the returning acoustic signal also reflect the pulse duration. The pulse duration is the period of time the sounder transmits power to the transducer. It is directly proportional to the amount of acoustic energy propagated into the water. A very short pulse duration (<200 μs) does not deliver enough energy to the seabed, resulting in a backscatter with less information, whereas a long pulse duration (500 μs), originates a backscatter with more classification information. It is important to notice that to long pulse duration may cause ping collision, in other words, the collision between the transmitted and the returned acoustic signals, which will affect the quality of the received echo (Collins and Rhynas, 1998).

The selection of an appropriate power setting for the echo sounder, which can be controlled by the operator, is an important step in the acoustic survey approach since it maximizes the capabilities of the sounder, preventing the loss of signal strength in soft or deep seabeds and diminishing the signal clipping in shallow areas. Also this feature of the acoustic system will influence the information returned from the seabed (Collins and Rhynas, 1998).

Unlike pulse duration and transmit power, the frequency of the acoustic pulse emission, known as ping rate, does not affect the characteristics of the return acoustic signal. However, to fast repetition rates and slow vessel speeds can create redundant data while to slow ping rates in deep water combined with fast vessel speeds can create gaps in the coverage of the survey area. In deep waters a fast ping rate can also cause ping collisions (Collins and Rhynas, 1998).

The transducer beam width is a measure of the conical shaped path of the transmitted echo pulse. The size of the seabed acoustic footprint, and consequently the resolution cell size for each data record, is a function of the beam width and the water depth. Therefore, higher beam widths will originate bigger footprints resulting in low-resolution acoustic classification. This problem increases with water depth (Collins and McConnaughey, 1998).

Beyond the influence of the mentioned configuration factors, the characteristics of the returned acoustic signal are mainly determined by the nature of the seafloor and immediate subsurface (Lurton and Pouliken, 1992; Collins et al., 1996). The physical properties of the sediments are of prime importance. These include textural information (as grain size), condition of state (as compactness and density), seabed roughness and sedimentary bedforms (as ripple marks) (Collins et al., 1996).

The extent to which the acoustic pulse is absorbed and reflected depends on the hardness of the seafloor; hard surfaces produce stronger echoes whilst soft surfaces produce weaker signals (Collins et al., 1996; Collins and Galloway, 1998; Collins, 1999). The energy reflected from a rough complicated seabed exhibits a high degree of backscatter and the echo trace resulting from this type of bottom has a wide peak and a tail (Figure 1). The acoustic signal from a smooth simple muddy seabed, which absorbs a high amount of energy, exhibits a low degree of backscatter giving rise to an echo trace with a relatively narrow peak and no tail (cf. Figure 1) (Collins et al., 1996; Collins and Galloway, 1998; Collins, 1999). Weak echoes are also obtained from the seafloor areas ensonified by the sound energy that spreads away from the centre of the sound cone. This energy takes slightly longer to reach the seabed because of the extra distance travelled, and this time lag is proportional to the angular distance away from the vertical axis of the transmited pulse (Lurton and Pouliquen, 1992).

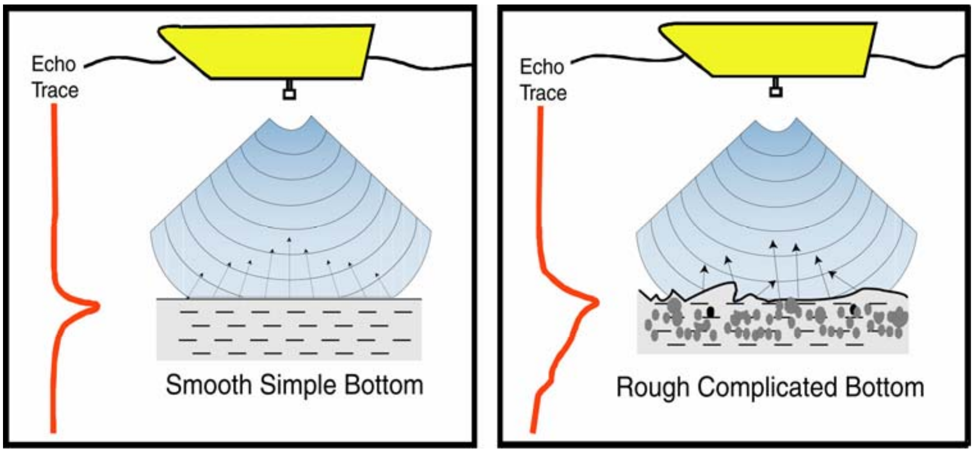


Figure 1. Schematic representation of two hypothetical seabeds and corresponding echo traces (adapted from Collins et al., 1996).

Over the last years, several seabed mapping and characterisation applications have been done using the acoustic ground discrimination system QTC VIEW. The successful use of this acoustic system is due to its ability to respond to the physical properties of the surveyed seabeds and give a valid interpretation according to both acoustic classification and ground-truth (Figure 2).

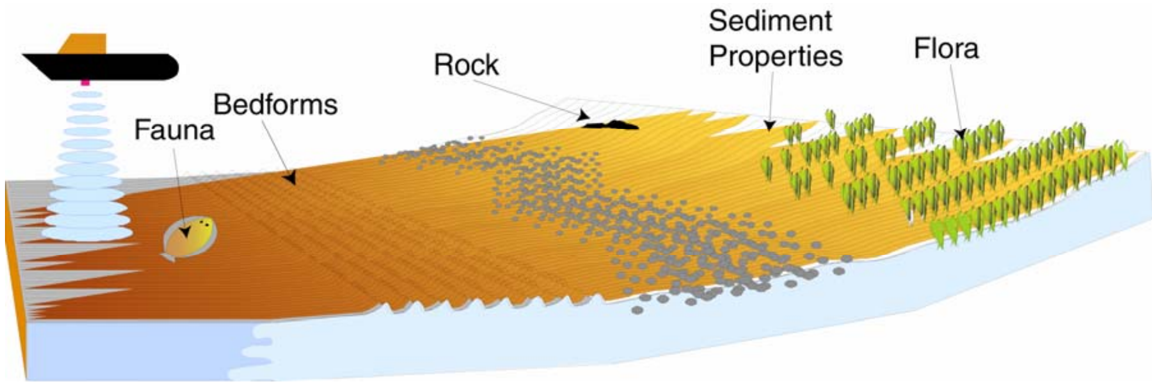


Figure 2. Seabed characteristics that influence the echo (adapted from Collins and Galloway, 1998).

On the last decade, works done worldwide have shown that the acoustic information obtained by the QTC VIEW system reflects a number of seabed characteristics, such are sediment grain size, seabed roughness, density difference between the water and the seabed material, seafloor sediment texture, sediment porosity and bottom slope, (Collins et al., 1996; Collins and Lacroix, 1997; Collins and Galloway, 1998; Hamilton et al., 1999; Preston et al., 1999; Bornhold et al., 1999; Ellingsen et al., 2002; von Szalay and McConnaughey, 2002). Several works concerning benthic habitats mapping and characterisation demonstrated that the presence/absence of algae, bivalve shells and some benthic species also influence the single-beam acoustic backscatter (cf. Figure 2) (Smith et al., 2001; Morrison et al., 2001; Self et al., 2001; Anderson et al., 2002).

Through these works, among others, and with the knowledge that physical properties of the environment, such as sediment type, are important for the species spatial distribution, the use of the acoustic system QTC VIEW has become more common in the characterisation and mapping of benthic communities and biotopes within impact assessment, conservation, and ecological patterns and processes studies.

Recent work concerning the remote sensing of benthic biotopes, among which are included the studies developed during this thesis, has shown the advantages of the joint use of the QTC VIEW acoustic system with ground-truth conventional grab sampling methods, as it can provide a detailed large-scale distribution pattern of benthic habitats in much less survey time than the point based conventional sampling approaches (Freeman and Rogers, 2003; Freitas et al., 2003a; 2003b; 2005; Foster-Smith et al, 2004; Freeman et al., 2004; Hewitt et al., 2004; Mackinson et al., 2004; Hutin et al., 2005; Riegl and Purkis, 2005).

The performance of this acoustic approach for impact assessment of anthropogenic activities, such as dredging of shipping channels, was recently tested with success by Wienberg and Bartholomä (2005). However, this type of studies remains relatively unexplored.

1.3 Aims of this thesis

The work presented in this thesis aimed to evaluate the efficiency of the acoustic ground discrimination system QTC VIEW for the remote identification/characterisation and mapping of sublittoral benthic biotopes under a suite of contrasting environmental conditions. The general methodology employed was based on the analysis and interpretation of the QTC VIEW backscatter combined with sediment and benthic macrofaunal analysis. The work covered a wide depth range (5-200 m) and a high variety of seabed habitats (coastal shelf, bar channels, lagoon), sediment types and benthic communities.

The acoustic surveys employed the QTC VIEW Series IV and Series V in the lagoon of Óbidos, the entrance channel of Ria the Aveiro, a near shore shelf area off Aveiro, a mid shelf area off Lisbon and the continental shelf off Aveiro. These study areas were selected with the intention to cover as much as possible a high diversity of benthic habitats and contrasting use conditions.

The lagoon of Óbidos was chosen in order to evaluate the performance of the acoustic system (QTC VIEW Series V) in an area characterised by very shallow water depth and high diversity of macrofauna communities and sediment types. The survey conducted in the entrance channel of Ria de Aveiro also represents a relatively shallow area for the acoustic system employed (QTC VIEW Series IV) and has the particularity of being characterised by a well-defined variety of sediments types which result from high hydrodynamic processes that influence this area. Since the use of conventional sampling methodologies using grabs or corers is difficult in this environment due to the strong tidal currents and intense ship traffic, the acoustic system could be a suitable alternative approach. The near shore shelf off Aveiro was also chosen due to the fact that this area is characterised by a gentle slope and a relatively monotonous soft-bottom, with no highly three-dimensional features such as bedrocks or biogenic structures. The survey here was conducted up to 35 meters depth, for which the superficial sediments always presents a very low percent content of the silt and clay fraction but supports two very contrasting benthic communities, namely a fine/very fine sand and a gravely sand community, with almost no common species. The mid shelf off Lisbon represents an area extending from 30 to 90 meters, with a steeper slope and a mixture of sediments ranging from clean fine sand to mud with very high silt and clay content. The area shows a smooth fines increase of the superficial sediments along the depth gradient, over which the macrofauna exhibits a gradual replacement of the dominant species. Finally, the survey conducted on the continental shelf off Aveiro, extending from the near shore up to 200 meters depth, aimed to study the efficiency of the acoustic system in a large spatial scale and full shelf depth range using the same baseline settings for the acoustic system.

CHAPTER 2 – MATERIAL AND METHODS

2. Material and methods

2.1 Sampling

2.1.1 Lagoon of Óbidos

The Lagoon of Óbidos, located on the western coast of Portugal, presents a mean water depth of 2 m and communicates with the ocean through a narrow channel. With an area of approximately 7 km^2, this lagoon is characterised by a wide variety of superficial sediment types (from mud to very coarse sands) and high benthic macrofauna species abundance and richness (Quintino et al., 1989).

The acoustic survey was run with the QTC VIEW Series V and covered the entire lagoon (Figure 3).

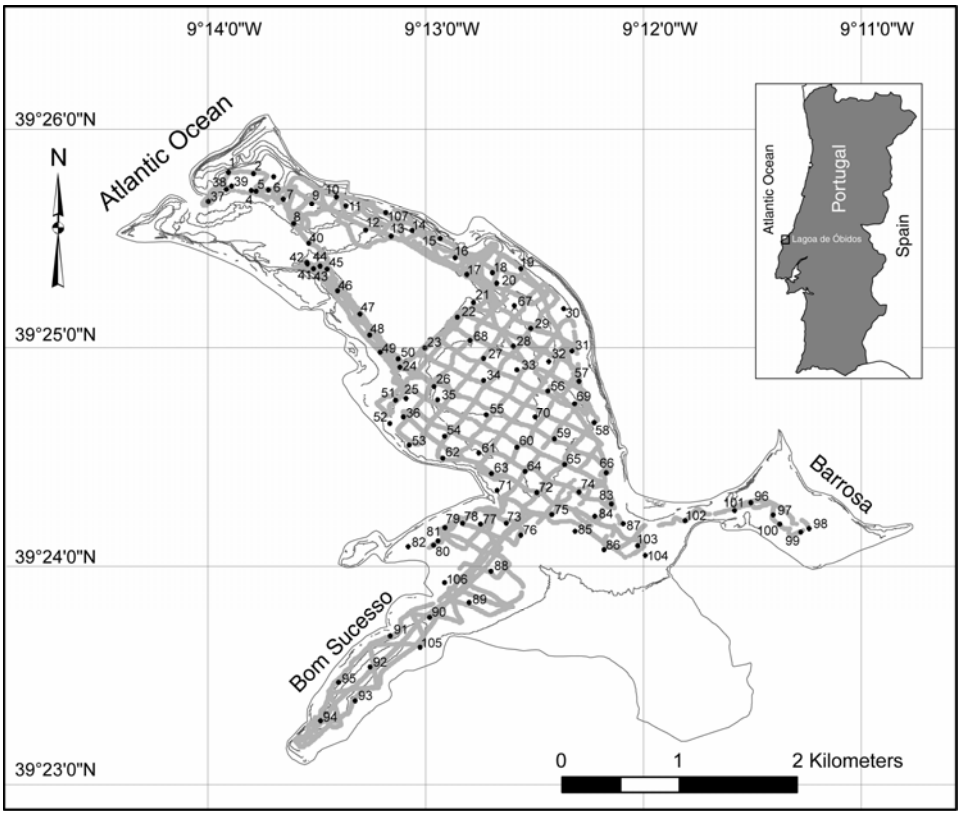


Figure 3. Lagoon of Óbidos. Study area showing the acoustic survey lines from QTC VIEW Series V and the sampling sites for the study of superficial sediments and benthic communities (numbered 1 to 107).

The acoustic seabed classification system was connected to a 50 kHz echo sounder with a transducer mounted on the side of a small fishing boat (Figure 4). The echo sounder and the QTC VIEW base settings are presented in Table 1. A differential Global Position System (DGPS) acquired the positioning, which was logged continuously along with the acoustic data and depth. The acoustic system also includes a laptop computer for data acquisition, display and storage. Due to the small size of the survey boat (cf. Figure 4), to diminishing interferences coming from the engine, the transducer was mounted at the side of the boat as far as possible from turbulence caused by this apparatus and the survey speed did not exceed 4 Knots. To evaluate the feasibility of the acoustic classification the survey lines were intersected (cf. Figure 3).

Figure 4. Boat used for the acoustic survey at the Lagoon of Óbidos.

Ground-truth sediment samples were collected with a 0.05 m^2 PONAR grab, in 107 sites (cf. Figure 3). These sites were intentionally positioned over the acoustic survey lines and spread over the entire surveyed area in order to cover the whole range of acoustic classes identified. At each site, 2 sediment samples were collected: one for the study of sediment properties and the other for macrofaunal community analysis. The macrofauna samples were washed in the field, over a 1 mm mesh screen and the remaining material was fixed in 4% buffered formalin, and stained with Rose Bengal. Redox potential and temperature were measured on board at each sampling site. Redox potential was determined at approximately –4 cm from the sediment surface with specific probes before emptying the grab sample (Pearson and Stanley, 1979).

Table 1. Lagoon of Óbidos. Survey base settings for the echo sounder and the QTC VIEW (Series V). AGC = Automatic Gain Control.

	Parameter	Setting
Echo sounder	Beam width	19°
	Transmit power	100 Watt
	Pulse duration	300 μs
	Ping rate	5 per second
	Frequency	50 kHz
QTC VIEW	Base gain	AGC

Sediment photographs were taken at each sampling site in order to define algae abundance classes over the study area (Figure 5). The classes were defined through visual observation of the percent cover of algae in each sampling site: absence, corresponds to sites where no algae were found; low, corresponds to a percent cover of algae below 25% of the unit sampling area; medium, corresponds to a percent cover of algae between 25 and 50%; high, corresponds to a percent cover of algae above 50% of the unit sampling area. This scale was used to compare the acoustic classes to the algae patterns that characterise the lagoon of Óbidos.

Figure 5. Photographs of the superficial sediment layer characterised by different algae cover: Absence, corresponds to sites where no algae were found; Low, Medium and High cover correspond to, respectively, ≤ 25%, 25-50% and ≥ 50% of the unit sampling area covered by algae.

The QTC VIEW Series V is the most recent in the QTC VIEW line series and was specifically developed to enable accurate classification in very shallow water (QTC VIEW Series V, 2002). In comparison with the QTC VIEW Series IV, Series V represents an advance in signal acquisition by increasing the rate for sample digitisation, sample resolution and dynamic range (i.e. the amount of acoustic signal amplification). This results in an increase in operating water depths and an ability to implement a new method of compensation for changes in echo length with depth. The Series V acquires and logs the complex waveform as raw data in contrast to the pre-processed set of echo descriptors obtained by Series IV. QTC VIEW Series V logs the data for post-processing only, whereas Series IV has the capability of real-time classification. Moreover, Series V has the capability of real-time echo trace viewer, providing excellent quality assurance during data acquisition (QTC VIEW Series V, 2002). This same ability was only recently developed for the QTC VIEW Series IV, through software development (QTC VIEW Series IV, 2004)

A comparison between the most important characteristics of QTC VIEW Series V and Series IV is presented in Table 2.

Table 2. Comparison of QTC VIEW Series IV and QTC VIEW Series V.

Parameter	**Setting**	
	QTC VIEW Series IV	**QTC VIEW Series V**
Sample rate	20 kHz	5000 kHz
Resolution	8 bits	12 bits
Dynamic range	60 dB (Manual Gain)	+80 dB (Automatic Gain Control)
Depth range	10 – 500 m	0.75 – 2000 m
Depth compensation	Manual Reference Depth Selection	Automatic Standard Echo Length
Raw Data	Feature Vectors	Full bi-polar waveform, interpolated envelope
GPS Input	GGA or GLL, 4800 Baud	GGA, GLL, RMC Custom unlimited d Baud
Acoustic classification	Real time and Post-processing	Post-processing
Quality Assurance/Quality Control during acquisition	Off line waveforms, real-time manual water depth check	Real-time waveform visualisation and depth pick

2.1.2 Entrance channel of Ria de Aveiro and near shore shelf

Ria de Aveiro is a complex coastal lagoon, located on the western coast of Portugal, and connected to the Atlantic ocean by a permanent artificial channel (Figure 6). Narrow navigation channels and extensive intertidal zones characterize this complex system. During spring tides, the maximal wet area varies from 66 km^2 at low tide and 83 km^2 at high tide (Dias et al., 2000). The tidal range varies between 0.6 m at neap tides and 3.2 m at spring tides, with an average of about 2 m (Dias et al., 2000).

The study area covered approximately 16 km^2 and included the narrow entrance channel of Ria de Aveiro and the adjacent near shore shelf (cf. Figure 6). The survey depth ranged mainly from 5 to 15 m, occasionally reaching 25 m only in very specific areas located across the entrance channel, dug by strong tidal currents of over 3 m/s (Dias et al., 2000; 2003).

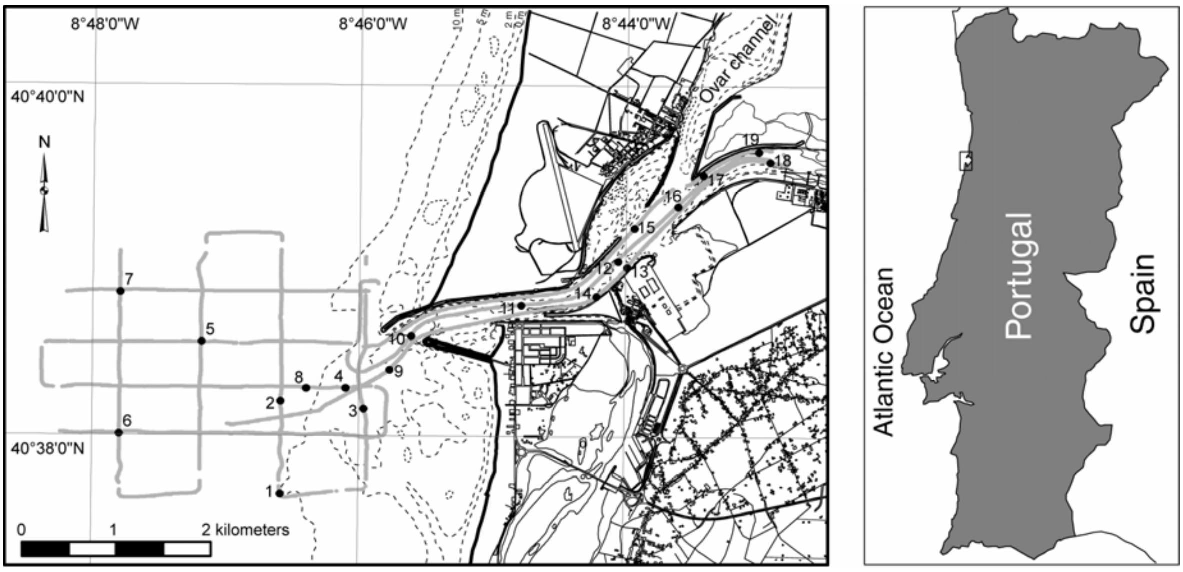


Figure 6. Entrance channel of Ria de Aveiro and near shore shelf. Study area showing the acoustic survey lines from QTC VIEW Series IV and the sampling sites for the study of superficial sediments (numbered 1 to 19).

The acoustic survey was conducted with a QTC VIEW Series IV connected to a 50 kHz echo sounder. The transducer was mounted on the side of the research vessel "N.R.P. Andrómeda" (Figure 7). A laptop was used for data acquisition, display and storage, and a Global Position System (DGPS) allowed acquiring the coordinates of the echoes. The echo sounder and QTC VIEW settings are presented in Table 3. In the near shelf, regular survey lines were positioned delineating a grid, whereas in the narrow entrance channel, the survey comprised transects positioned along the navigation channel (cf. Figure 6).

Ground-truth samples for sediment grain-size analysis were obtained using a 0.1 m^2 Smith-McIntyre grab. Samples were collected at 19 sites, the positioning of which was delineated as soon as a preliminary classification of the acoustic data was obtained, in order to optimise sampling effort (cf. Figure 6).

Figure 7. Research vessels “N.R.P. Auriga” (left) and “N.R.P. Andrómeda” (right).

Table 3. Entrance channel of Ria de Aveiro and near shore shelf. Survey base settings for the echo sounder and the QTC VIEW (Series IV).

	Parameter	Setting
Echo sounder	Pulse duration	300 μs
	Beam width	19°
	Transmit power	100 Watt
	Range	0 - 60 m
	Ping rate	5 per second
QTC VIEW	Base gain	10 dB
	Depth	Maximum: 40 m
		Minimum: 5 m
		Reference: 10 m

2.1.3 Near shore shelf off Aveiro

In the near shore off Aveiro, the acoustic survey covered approximately an area of 500 km^2, with water depth ranging from 5 to 40 m (Figure 8).

This study area is characterised by a range of grain-size sandy and gravel sediments, all with very low silt content. The bathymetry follows a gentle slope, without the presence of highly three-dimensional features such as bedrock, algal beds and biogenic structures.

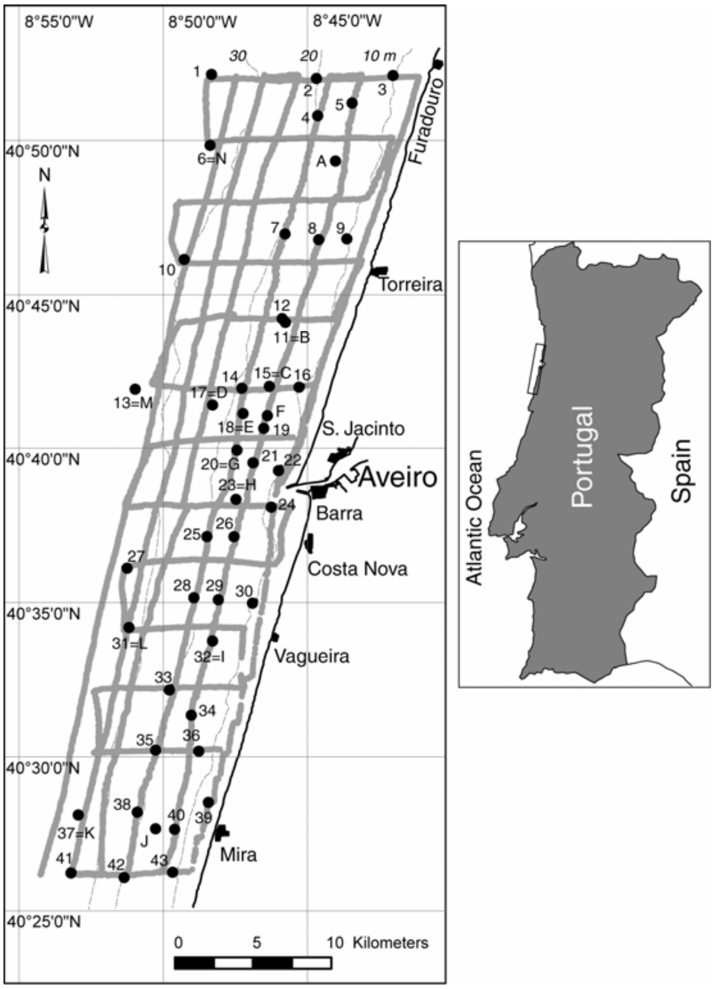


Figure 8. Near shore shelf off Aveiro. Study area showing the acoustic survey lines from QTC VIEW Series IV and the sampling sites for the study of superficial sediments (numbered 1 to 43) and benthic communities (named A to N).

The acoustic survey was run with the QTC VIEW Series IV, using a 50 kHz echo sounder. The acoustic data acquisition was conducted aboard the vessel “Ciclone” (Figure 9), at an average speed of 6 knots. The survey grid comprised a total of 13 lines with length between 7 and 12 km, oriented east to west and placed 3.5 km apart to cover the study area (cf. Figure 8). For quality assurance, 6 lines, approximately 50 km long, were placed perpendicular to the previous ones (cf. Figure 8).

The acoustic system includes a laptop computer for data acquisition, display and storage, and a differential Global Position System (DGPS) that provides positioning. The echo sounder and QTC VIEW final settings are given in Table 4.

Figure 9. Life-boat “Ciclone” used for the acoustic survey at the near shelf area off Aveiro.

To minimize possible interference from the operating environment, such as noise from other equipment and from the survey vessel, the acoustic system was run with an autonomous power source and all other vessel sounders were turned off during the survey.

Table 4. Near shore shelf off Aveiro. Survey base settings for the echo sounder and the QTC VIEW (Series IV).

	Parameter	Setting
Echo sounder	Pulse duration	360 μs
	Beam width	44°
	Transmit power	150 Watt
	Range	0 - 40 m
	Ping rate	5 per second
QTC VIEW	Base gain	15 dB
	Depth	Maximum: 75 m
		Minimum: 3 m
		Reference: 25 m

Ground-truth sediment samples for grain-size analysis were taken at 43 sites, using a 0.1 m^2 Smith-McIntyre grab, at the end of the acoustic survey (cf. Figure 8). The sites were positioned to cover as much as possible the whole range of acoustic classes identified in the survey, most of them intentionally positioned on the acoustic survey lines (cf. Figure 8). Data on macrofaunal communities was collected from 14 sites (3 grab replicates per site), prior to the acoustic survey (letters, A to N in Figure 8). These samples were washed on board over a 1 mm mesh screen and the remaining material was fixed in 4% buffered formalin and stained with Rose Bengal. The sampling sites for the study of the benthic communities coincide with those for the sediment grain-size analysis, with the exception of sites A, F and J (cf. Figure 8), for which the sedimentary data was already available. All the grab samples were collected using the research vessel “N. R. P. Auriga” (cf. Figure 7). Grab sampling was limited, by the sea state and the size of “N.R.P. Auriga”, to waters deeper than 10 m, with the exception of one site (39). The smaller and more manoeuvrable vessel “Ciclone” (cf. Figure 9) was able to access the area adjacent to the surf zone closer to shore, during limited periods of calm sea conditions, but only for the acoustic survey.

2.1.4 Continental shelf off Aveiro

The least steep slope of the Portuguese continental shelf is obtained off Aveiro, where the 200 meters contour line is located at approximately 60 km from the coastline. This area was chosen to run an acoustic survey covering the full depth range of the shelf, using the same QTC VIEW base settings.

The acoustic survey comprised 6 transects perpendicular to the coast and 2 oblique to the previous for quality assurance (Figure 10). This survey grid covered approximately 2400 km^2 and was positioned according to the location of the sampling sites from a previous benthic communities survey in this shelf area (Moreira et al., 2001).

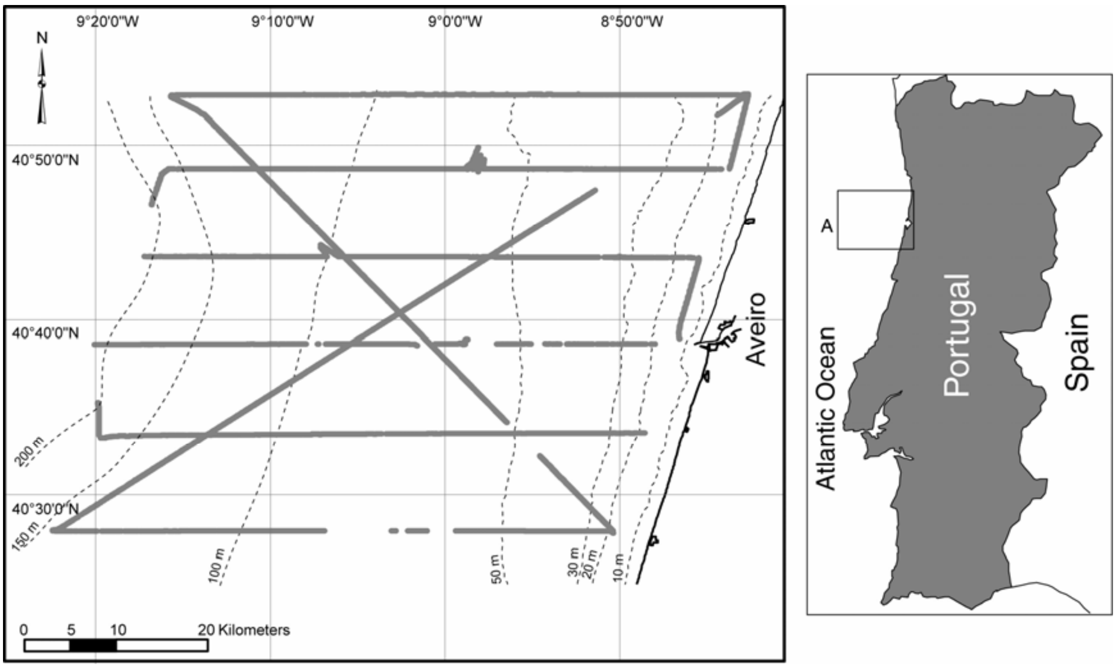


Figure 10. Continental shelf off Aveiro. Study area showing the acoustic survey lines from QTC VIEW Series IV.

The survey was conducted with a QTC VIEW Series IV connected to a 50 kHz echo sounder, with the transducer mounted on the side of the research vessel "N.R.P. Andrómeda" (cf. Figure 7). A laptop was used for data acquisition, display and storage, and a differential Global Position System (DGPS) allowed to acquire the coordinates. Table 5 presents the echo sounder and QTC VIEW base settings used in the survey. The 0-60 m depth range was selected for the echo sounder. At this range, the pulse duration for the echo sounder used in the survey (cf. Table 5) is short (300 μs), which has advantages when sampling at the lower depth. At the 0-80 m depth range the echo sounder more than doubles the pulse duration (800 μs) and with a depth range of 0-200 m the pulse duration is four times longer (1200 μs). However, using the sounder with the 0-60 m depth range introduces a problem with the ping rate, 5 per second, which produces two pings in the water, simultaneously, at depth above 150 meters. Because QTC VIEW Series IV uses a depth windowing process for bottom pick, this will not affect the data collected for the acoustic classification. This automatic filtering in QTC VIEW IV is effective and normally will exclude most of the bottom pick problems. Nevertheless, the data were reviewed in order to ensure that only echoes with the correct bottom pick were considered for the acoustic classification procedure.

Table 5. Continental shelf off Aveiro. Survey base settings for the echo sounder and the QTC VIEW (Series IV).

	Parameter	**Setting**
Echo sounder	Pulse duration	300 μs
	Beam width	19°
	Transmit power	100 Watt
	Range	0 - 60 m
	Ping rate	5 per second
QTC VIEW	Base gain	10 dB
	Depth	Maximum: 150 m
		Minimum: 25 m
		Reference: 70 m

In this study area no ground-truth samples were obtained. The acoustic pattern was interpreted through comparison with data from previous works conducted on the same area by other authors (Abrantes et al., 1994; Moreira et al., 2001).

2.1.5 Mid shelf off Lisbon

The area surveyed in the mid shelf off Lisbon (western coast of Portugal) (Figure 11) is characterised by soft bottom, where neither bedrock nor algae mats occur, and where the sedimentary environment exhibits a smooth gradient, although encompassing a wide range of sediment grain-size, from clean fine sand to mud.

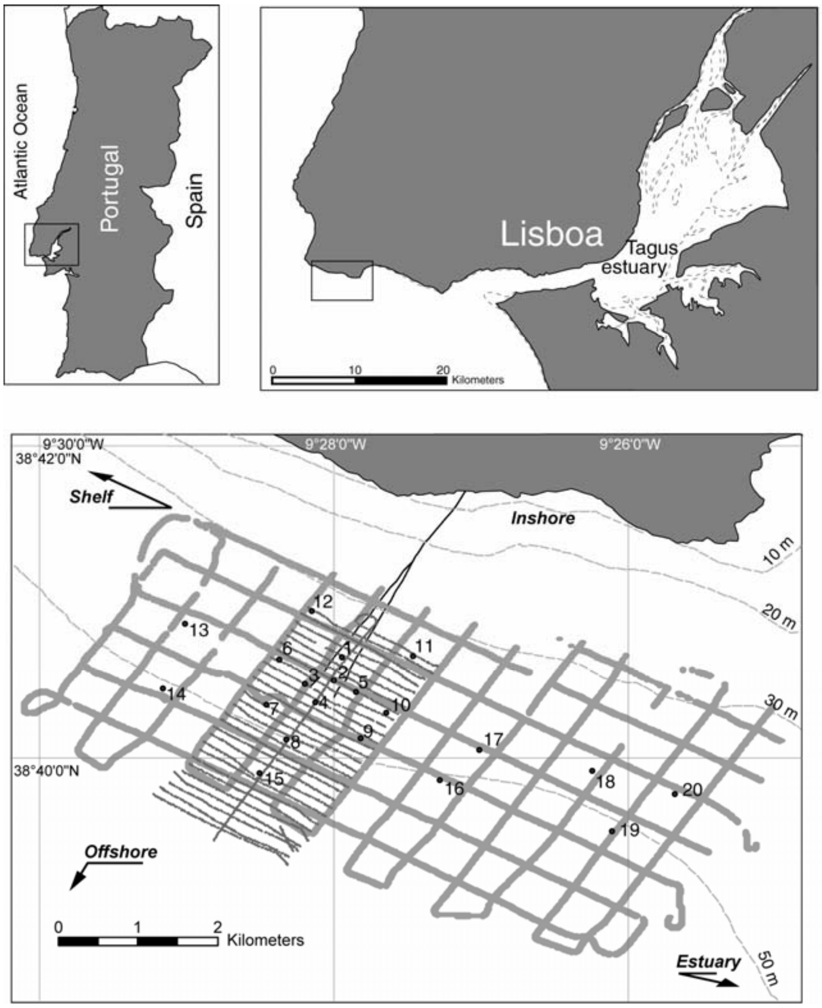


Figure 11. Mid shelf off Lisbon. Study area showing the acoustic survey lines from QTC VIEW Series IV (larger area) and Series V, the sewage outfall branches and the sampling sites for the study of superficial sediments and benthic communities (numbered 1 to 20).

The acoustic survey was done with two single-beam ground discriminating systems operating separately: QTC VIEW Series IV and Series V. The QTC VIEW Series

IV was used in an area comprising approximately 20 km^2 (cf. Figure 11), with depth ranging from 30 to 90 m. The survey lines were run aboard the research vessel “N.R.P. Andrómeda” (cf. Figure 7), with approximately 500 m spacing throughout the survey area (cf. Figure 11). This acoustic system was connected to a 50 kHz echo sounder and a transducer beam width of 44º (Table 6). The QTC VIEW Series V was used over part of the previous area and using a denser spatial grid: the survey lines were spaced approximately 100 m (cf. Figure 11), covering an area closer to the outfall branches, and run aboard the research vessel “N. R. P. Auriga” (cf. Figure 7). This acoustic system was also connected to a single beam echo sounder operating at 50 kHz, but in this case the transducer beam width was 19º (cf. Table 6). In both surveys the transducer was fixed to the right side of the vessel and the survey speed was kept close to 6 knots. Positioning was confirmed with a differential Global Position System (DGPS), which provided data for navigation and to be logged with the seabed classification data for representation in a GIS. Both acoustic systems include a laptop computer for acquisition, display and storage of the acoustic information. To ensure noise from other equipment would not interfere with the echoes acquired, all the vessel’s sounders were turned off during the survey.

Table 6. Mid shelf off Lisbon. Survey base settings for both echo sounders and acoustic systems. AGC = Automatic Gain Control.

	Parameter	**Setting**	
		QTC VIEW Series IV	**QTC VIEW Series V**
Echo sounder	Pulse duration	625 μs	300 μs
	Beam width	44°	19°
	Transmit power	150 Watt	100 Watt
	Range	0 -100 m	0 -100 m
	Ping rate	5 per second	5 per second
QTC VIEW	Base gain	5 dB	AGC
	Depth	Maximum: 100 m Minimum: 30 m Reference: 50 m	Maximum: 100 m Minimum: 30 m Reference: 50 m

Ground-truth sediment samples were initially taken at 20 sites, for the study of sediment properties and macrofaunal communities (cf. Figure 11). A 0.1m^2 Smith-McIntyre grab was used, and 5 replicates per site were collected, 2 for sediment characterisation and 3 for faunal analysis. The macrofauna samples were washed on board over a 1 mm mesh screen and the remaining material was fixed in 4% buffered formalin, stained with Rose Bengal. Redox potential was measure, on board, at each sampling site. This parameter was determined at approximately –4 cm from the sediment surface with specific probes before emptying the grab sample (Pearson and Stanley, 1979).

Once the acoustic diversity gradient become available, it was recognized that some areas were validated with one or few ground-truth sampling sites. A later validation survey was designed to achieve a better ground-truth spatial coverage. The sampling sites, a total of 60, were distributed over the acoustic gradient previously identified. The samples were obtained with a 0.1 m^2 Smith-McIntyre grab and, two per site, 1 for sediment and 1 for macrofaunal analysis. Sites 1 to 20 were located as in the previous assessment, and sites 21 to 60 were distributed in order to ensure a detailed coverage of all the study area. Figure 12 shows the positioning of the 60 sampling sites superimposed on both acoustic survey grids.

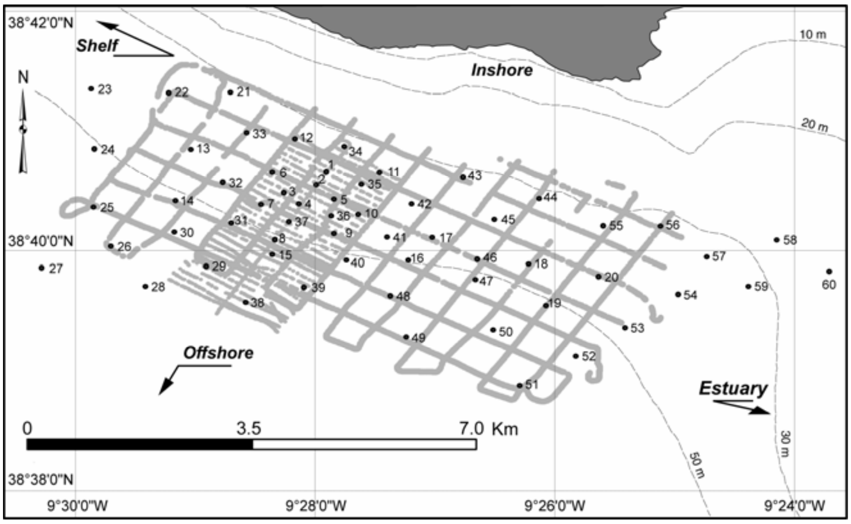


Figure 12. Mid shelf off Lisbon. Study area showing the acoustic survey lines from QTC VIEW Series IV (larger area) and Series V, the sewage outfall branches and the sampling sites for the study of superficial sediments and benthic communities (numbered 1 to 60).

2.2 Calibration of the acoustic system

In order to obtain high-quality acoustic data, the acoustic system was calibrated in every studied area, before starting each survey. This calibration permits to choose the best QTC VIEW parameters, such as the system base gain, which will allow a better acoustic acquisition over the entire area, independently of bottom type and depth.

With this purpose, at each study area and in various sites differing in sediment properties and depth, different base gain values were tested and a few echoes were acquired with the acoustic system, while the vessel was stationary. Base gain is the amount of amplification of the acoustic signal in preparation for digitisation (QTC VIEW Series IV, 2004). This setting ensures that seabed with significantly low reflectivity provides enough strength for analysis. This procedure was done at each site, testing different base gain settings. At each time, the echo waveform was analysed and depending on the characteristics observed from the echoes, a proper base gain was chosen, corresponding to the best echoes acquired (cf. Tables 3, 4, 5 and 6). When using the QTC VIEW Series V there is no need to select the best base gain since this system has the ability for, automatically, choose the best values when running the survey (cf. Tables 1 and 6).

The reference depth for each survey is also a crucial element when surveying with the QTC VIEW Series IV. It should reflect either the average survey depth or the depth at which most of the echoes are collected. As a rule of thumb, it is advisable not to include in the same survey a depth range higher and/or lower than four times the reference depth (i.e., for a reference depth of 60 m, data collected below 15 m and above 240 m may reveal depth related classification artefacts). This is due to the distortion produced by the normalisation of the echo to the reference depth, which will make the echo longer or shorter (Preston et al., 2004b; and personal communication).

After calibration, a configuration was chosen so that useable echoes were received over the full survey area, i. e. without clipping, or with to low energy level. To assess possible inference from the operating environment, such as noise from other equipment and from the survey vessel, raw echoes obtained at several sites were visualized in real time. To minimize such potential noise, the acoustic system was run with an autonomous power source and all other vessel sounders were turned off during the survey.

2.3 Laboratory analysis

2.3.1 Sediments

2.3.1.1 Grain-size

Grain-size analysis was performed by wet and dry sieving, according to the following steps (Quintino et al., 1989):

- Washing the sediment with distilled water followed by chemical destruction of organic matter with H_2O_2;
- Drying the sample at 110º C, until the obtention of a constant weight and determination of the total dry weight (=P1);
- Chemical dispersion of the sediment for 24 hours in tetra-sodium pyrophosphate (30g/l) and wet sieving through a 63 μm mesh screen;
- Measurement of the second dry weight of the material left on the mesh (=P2) and calculation of the dry weight of the fraction under 63 μm by difference (P1-P2);
- Dry mechanical sieving of the P2 fraction using sieves with mesh screens ranging from 63 μm (4ϕ) to 4 mm (-2ϕ), at 1ϕ intervals (ϕ= -$\log_2$ the dimension of the particle expressed in mm);
- Weighting the fractions retained in each sieve;
- Determination of the percent content of each fraction in relation to the total dry weight (excluding the biogenic fraction);
- Determination of the biogenic fraction, mainly composed by mollusc shells, in the grain-size fraction above 2 mm. This fraction was expressed as a percentage of the total dry weight of the whole sediment sample.

2.3.1.2 Total volatile solids

As mentioned before for the redox potential, the study of total volatile solids is important for the analysis of benthic macrofauna spatial distribution. The distribution of benthic organisms may be conditioned by the sediment content in organic matter and therefore, although this parameter should not influence the acoustic information, it was measured and used as an explaining variable for the distribution pattern of benthic communities.

For this analysis, the samples collected were preserved at –20º C. In the laboratory, after bringing to room temperature, the sediment samples were oven dried at 80º C and macerated. Total volatile solids were determined by loss on ignition, determining the weight difference between the dried samples at 80º C and the combusted samples at 450º C (Byers et al., 1978; Kristensen and Anderson, 1987).

2.3.2 Macrofauna

In the laboratory, sediment samples for the study of macrofaunal communities were processed individually. The samples were washed and the animals sorted, identified to the highest possible taxonomic level and counted with the help of binocular dissecting microscope and an optic microscope.

For each sample, a species list with the respective abundance was determined.

2.4 Data analysis

2.4.1 Acoustic data

The acoustic pulse, generated by the echo sounder, reflects from the seabed water interface and the material in the immediate subsurface and is received by the transducer. From the transducer, the reflected pulse is transferred to the data acquisition software (QTC VIEW), merged with the position data (acquired by the DGPS) and transmitted to the computer for display and post-processing. The QTC VIEW uses the shape of the first returning echo to characterise the seabed. Using a series of algorithms, a digital characterisation of the echo shape is produced, consisting of 166 elements (Collins et al., 1996). Through Principal Component Analysis (PCA), the QTC VIEW produces a reduced description of the echo, which comprises three values (Q1, Q2 and Q3). The three Q-values correspond to the first three PCA axes (Collins and McConnaughey, 1998).

Principal component analysis (PCA) is a mathematical procedure that transforms a number of (possibly) correlated variables into a (smaller) number of uncorrelated variables called principal components. The objective of principal component analysis is to reduce the dimensionality (number of variables) of the dataset but retain most of the original variability in the data. The first principal component accounts for as much the variability in the data as possible (Clarke and Gorley, 2001).

Using post-processing software, the QTC IMPACT™ (v3.20 and v3.40), the description of the echo, comprised by the Q-values, is submitted to cluster analysis (K-means statistics) to obtain acoustic classes. This clustering procedure aims to distribute different echoes into groups (clusters) in a way that those echoes within each cluster are more closely related to one another than echoes assigned to different clusters. In other words, the degree of association between two echoes is maximal if they belong to the same cluster and minimal otherwise. Thus, the classification of the echoes is based on a progressive splitting process where, initially, points from a single acoustic class are plotted in Q-space forming a cluster, defined as an ellipsoid. This cloud is then split into two and points from different acoustic classes will form different clusters (QTC IMPACT, 2004).

In all the studied areas the acoustic data were submitted to manual cluster analysis (QTC IMPACT v.3.20). However, in the case of Ria de Aveiro entrance channel study the acoustic data were also analysed using an auto-cluster procedure, a new approach of cluster analysis only available in the most recent QTC IMPACT version (3.40). This analysis aimed to compare the results obtained with the two classification procedures (manual and auto-cluster). The Auto Cluster procedure in QTC IMPACT v3.40 uses a simulated annealing K-means algorithm in order to find an optimal number of classes. The optimal number of classes is indicated on a graphical display and is reached when the Total Score is minimum (QTC IMPACT, 2004).

The clustering approach used by the QTC IMPACT is the K-means statistics. The general K-means aims to find K clusters in the data set, and the clusters are described by the mean positions of the cluster members. The process begins by guessing K means as new cluster centres. Each datum is then assigned to the closest centre. These cluster centres are not the mean positions of all the points assigned to that cluster, so they are recalculated. These new means are then used in another assignment step. The process continues until the means and the cluster memberships stabilize. With the K-means statistics (a variation of the K-means algorithm) the initial guess relies not only on K means, but also on K covariance matrices. The analysis process starts as mentioned above and each time the means have stabilised the covariance matrix of each cluster is recalculated. The process continues until the memberships, means and covariances have all stabilised (Preston et al., 2002).

During the splitting process the user has to choose which class to split next (class 1 or class n), how to split it (through the primary, secondary or tertiary axis) and when to stop splitting. To help on such decisions, at each split, a series of statistical measures are provided and are used as indicators of the optimal split level, namely the Total Score and the Cluster Performance Index Rate. The Total Score is the sum of scores of the individual classes and the Cluster Performance Index (CPI) measures the ratio of the distance between cluster centres and the extent of the clusters in the Q-space. Initially the Total Score decreases rapidly as a function of the split-level. Further splits lead to smaller changes in this descriptor. When the number of splits is plotted against Total Score, the inflection point of the resulting curve is an indication of the optimal splitting level (QTC IMPACT, 2004). CPI rate is based on the Cluster Performance Index (CPI) and is defined as CPI (n) = (CPI (n) – CPI (n-1)) / CPI (n-1). CPI generally increases as a function of the splitting level but the CPI rate tends to be maximum at the optimal split level (Kirlin and Dizaji, 2000). Total Score and CPI rate are the main aids in deciding the final classification to retain. However, as with any other classification procedure, further acoustic classes may be considered, as long as they are interpretable.

Each acoustic record in the final classification file contains date, time, latitude and longitude, depth, Q1, Q2 and Q3 values, class name, a confidence percentage and a probability percentage. The confidence value of a record is the probability that the record belongs to the class to which it has been assigned. It is a measure of the covariance-weighted distances between the position of the record in Q-space and the positions of all cluster centres (QTC IMPACT, 2004). The probability value of a record is based on the position of that record in Q-space and the characteristics of the class to which it has been assigned. It is a measure of closeness to the cluster centre, weighed by the covariance of the cluster in the direction of the record (QTC IMPACT, 2004).

Depending on the acquired acoustic information and for a more accurate analysis, in some cases, the output file from QTC IMPACT was submitted to a careful analysis and points with low confidence and/or probability level were eliminated. Thus, data from QTC IMPACT analysis were sorted first by the confidence level and values under 98% or 95% were deleted (mid shelf and continental shelf/Lagoon of Óbidos data, respectively). The resulting file was further sorted by the probability and values under 5% or 1% (continental shelf and mid shelf data, respectively) were ignored.

To produce acoustic diversity maps, the acoustic information resulting from the QTC IMPACT analysis was imported to the Geographical Information System Arc View v8.1 (Minami, 2000). For that purpose, the final output file from QTC IMPACT was opened in a spreadsheet and the following echo description fields were selected: latitude, longitude, class name, class confidence and class probability. The Geographical Information System produces maps where the different acoustic classes, obtained through the acoustic classification analysis, are spatially distributed. In the case of the mid shelf work, charts displaying the results from the QTC VIEW Series IV and Series V surveys were overlapped to easily compare the information given by the two acoustic systems.

2.4.2 Sediment grain-size

After laboratory treatment, the sediment was classified according to the Wentworth scale based in the median value (P50), corresponding to the diameter that has half the grains (by weight) finer and half coarser, and the percent content of fine particles (Table 7) (Doeglas, 1968; Larsonneur, 1977). The median value was obtained graphically, by tracing each individual sediment cumulative frequency curve on probability paper.

The final sediment classification adopted the description “silty” and “very silty” for those samples with a silt and clay fraction ranging from 5% to 25% and from 25% to 50%, respectively, of the total sediment (dry weight). In the case of the near shore shelf sediments, off Aveiro, following the nomenclature proposed by Willman (Pettijohn, 1975), coarse and very coarse sands were named pebbly sand and sandy gravel, if their gravel content was between 5-25% and 25-50% of the total sediment, respectively (dry weight).

Table 7. Sediment classification adapted from Wentworth (Doeglas, 1968) and Larsonneur (1977).

Median (ϕ)	Sediment classification		Fines content (%)		
			<5	5 - 25	25 - 50
(-1) - 0		Very coarse			
0 - 1		Coarse			
1 - 2	Sand	Medium	Clean	Silty	Very silty
2 - 3		Fine			
3 - 4		Very fine			
> 4	Mud			Above 50%	

The grain-size classes identified were used to produce spatial distribution maps of the sediment types identified, using the Geographical Information System Arc View v8.1 (Minami, 2000). These maps were overlapped with the acoustic diversity maps. This procedure aimed to confirm the spatial relationship between the sedimentary and the acoustic gradient.

The sedimentary data were further submitted to classification analysis, using the average clustering algorithm, and to ordination analysis, by non-metric multidimensional scaling (NMDS) or by principal components analysis (PCA). Classification and ordination analysis were performed with the software PRIMER v5 (Clarke and Gorley, 2001) and MVSP v3.12d (Kovach, 1999). In both cases the Normalized Euclidean distance was used to produce a distance matrix for submission to classification and ordination analysis. The Normalized Euclidean distance coefficient is very common in environmental data analysis because it allows treating together variables expressed in different units (Ludwig and Reynolds, 1988).

Concerning the average clustering algorithm, the cluster procedure aims to distribute different objects into groups (clusters) in a way that those objects within each cluster are more closely related to one another than objects assigned to different clusters. A hierarchical clustering was performed with the sedimentary data. In this case the data are not partitioned into a particular cluster in a single step. Instead, a series of partitions take place, which may run from a single cluster containing all objects to n clusters, each containing a single object. The average linkage refers to the distance between two clusters defined as the average of distances between all pairs of objects, where each pair is made up of one object from each group (Clarke and Warwick, 1994).

The method of non-metric multidimensional scaling (MDS) consists in building a “map” with the distribution of the samples, which attempts to satisfy all the conditions imposed by the rank similarity matrix, e.g. if sample 1 has higher similarity to sample 2 than it does to sample 3 then sample 1 will be placed closer on the map to sample 2 than it is to sample 3 (Clarke and Warwick, 1994). The diagram resulting from the ordination analysis is represented in two dimensions (horizontal and vertical axes) and includes the respective stress value (Clarke and Warwick, 1994). This value is a measure of the distortion associated with the representation of the multidimensional distance matrix in two dimensions. If it is below 0.10, the representation is considered very good. If it is above 0.30, the final diagram should not be considered a reliable representation of the distance matrix (Clarke and Warwick, 1994).

Using the Geographical Information System Arc View v8.1 (Minami, 2000), the affinity groups obtained were used to produce the spatial distribution maps of the sedimentary data, which were overlapped with the respective acoustic diversity maps. This procedure aimed to verify the spatial consistency between the sedimentary and the acoustic gradient.

In the case of the continental shelf off Aveiro survey, no ground-truth samples were obtained and, therefore, the information about sedimentary characterisation of this area was made using published papers (Abrantes et al., 1994).

2.4.3 Macrofauna

Classification and ordination analysis were used in the analysis of the macrofauna data, using the software PRIMER v5 (Clarke and Gorley, 2001) and the software MVSP v3.12d (Kovach, 1999).

The biological data were square root transformed and a similarity matrix between sampling sites was obtained by applying the Bray-Curtis coefficient. This coefficient is one of the most commonly used in ecology and ranges between 0, when two sites have no common species, and 1, when two sites have the same species with the same abundance (Ludwig and Reynolds, 1988; Clarke and Warwick, 2001).

The classification analysis was done by average clustering while the ordination was obtained by correspondence analysis after square root transformation of the abundance data. The Square-root transformation has the effect of down-weighting the importance of the highly abundance species, so that similarities depend not only on their values but also on those of less common species (Clarke and Warwick, 2001).

The correspondence analysis (CA) is an ordination method, which implies a matrix of species x abundances. With CA, two-dimensional plots (one set for species and the other for sites) are produced showing variance within data sets. In the final diagram, the sites which share many species are plotted close to each other, whilst those with few species in common are plotted furthest apart.

As with the sedimentary data, through the Geographical Information System Arc View v8.1 (Minami, 2000), the biological affinity groups were used to produce the spatial distribution maps of the biological data. These maps were overlapped with the acoustic diversity maps to verify the spatial consistency between the biological and the acoustic gradient.

Concerning the Lagoon of Óbidos only the abundance of molluscs was used to produce spatial distribution maps, using the Geographical Information System Arc View v8.1 (Minami, 2000).

In the case of the continental shelf off Aveiro data, the comparison between the biological and the acoustic information was done using biological data from previous works (Moreira et al., 2001).

CHAPTER 3 - RESULTS

3. Results

3.1 Lagoon of Óbidos

3.1.1 Acoustic pattern

The results from the acoustic classification, obtained with the manual cluster analysis, are shown in Table 8.

Table 8. Lagoon of Óbidos. Acoustic classification statistics obtained by manual clustering up to the fifth split (six classes). Total Score = sum of the scores of the individual classes; CPI = cluster performance index; CPI rate = [CPI (n) – CPI (n-1)] / CPI (n-1), where n is the split number.

Split	Number of classes	Total Score	CPI	CPI rate
0	1	42215830.67	_	_
1	2	4871714.72	2.31	_
2	3	1831122.76	8.14	2.52
3	4	1435223.62	16.08	0.98
4	5	901581.67	52.34	2.25
5	6	556865.18	102.53	0.96

Following the indication provided by statistical descriptors such as CPI rate and Total Score, the optimal classification corresponds to the second split (three acoustic classes), where the CPI rate reaches the maximum value (cf. Table 8) and the Total Score tends to level (Figure 13 and cf. Table 8). Total Score decreases abruptly at the first split level (two acoustic classes) and tends to level at the second split (three acoustic classes), after which the reduction in Total Score values shown in Table 8 become imperceptible in the graph of Figure 13. Thus, optimal classification may consider three classes (Class A, B and C), corresponding to the second split level.

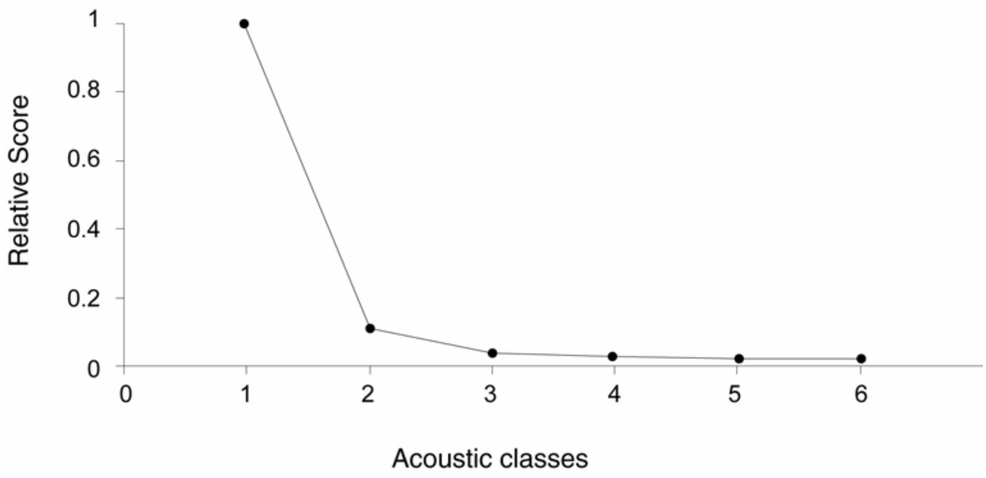


Figure 13. Lagoon of Óbidos. Relative score, expressed as standardized values for the Total Score obtained with one acoustic class.

The spatial distribution of the acoustic classes selected (A, B and C) is presented in Figure 14.

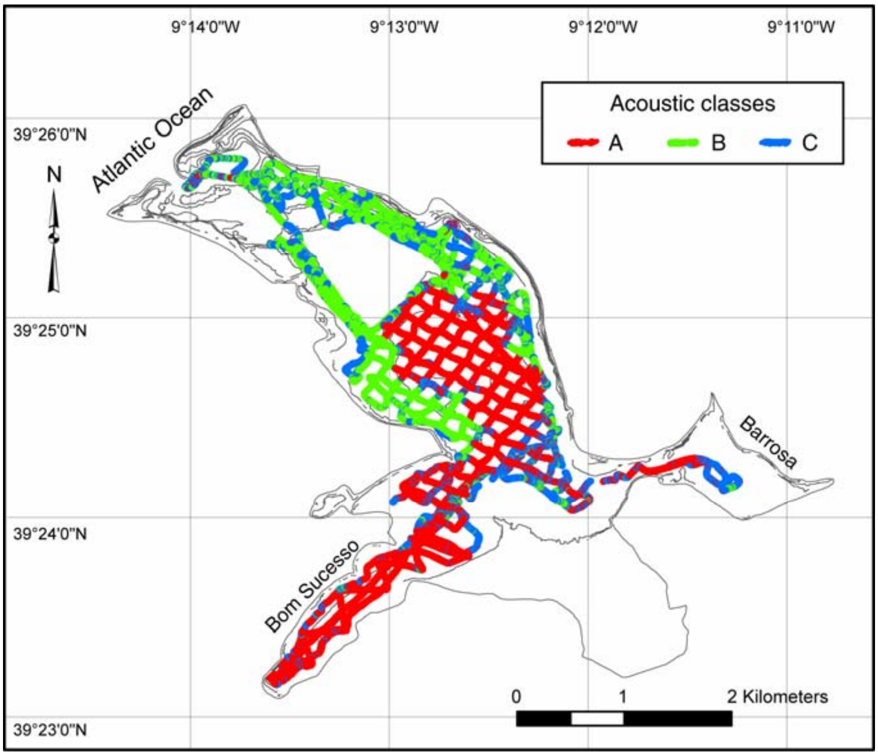


Figure 14. Lagoon of Óbidos. GIS representation of the acoustic pattern.

The acoustic class A appears predominantly in the centre of the lagoon and in the Bom Sucesso arm; class B characterises the navigation channels and the south margin of the lagoon central body; and class C, constituted by fewer members, is spread all over the lagoon, particularly near the margins.

3.1.2 Ground-truth

The results from the grain size analysis are presented in Table 9. Table 10 shows, for each sampling site, the information relating to the biogenic fraction, total volatile solids, redox potential, temperature, algae and molluscs abundance. Figure 15 presents the spatial distribution of the different sediment types identified.

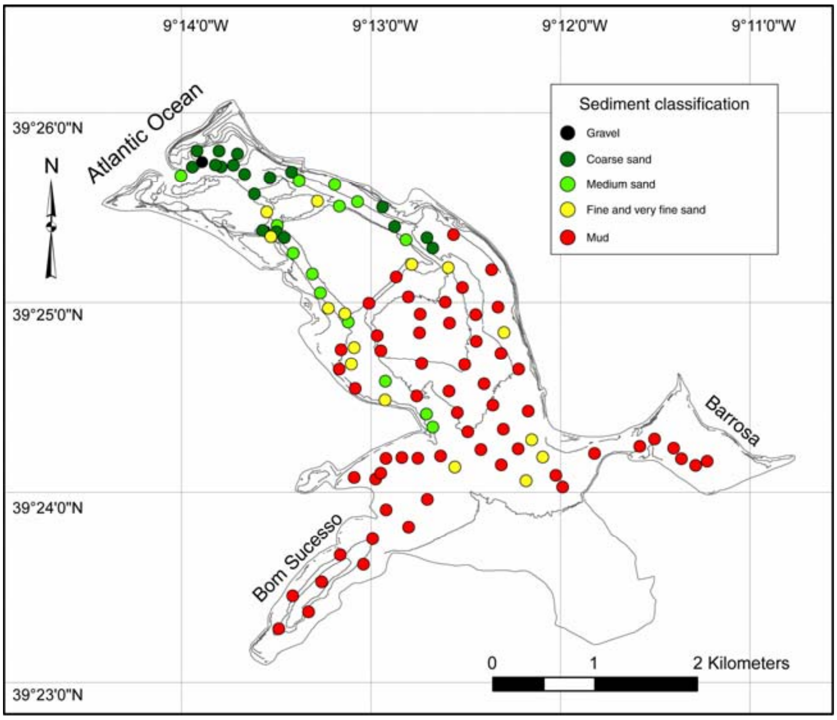


Figure 15. Lagoon of Óbidos. GIS representation of the five sediment types identified.

Table 9. Superficial sediment grain-size analysis from Lagoon of Óbidos. Grain-size classes (in mm) values are expressed as percent of total sediment dry weight, median value in phi units (Φ) and sediment classification according to Table 7.

Site	> 4.0 (%)	2.0-4.0 (%)	1.0 – 2.0 (%)	0.5 – 1.0 (%)	0.250 – 0.500 (%)	0.125 – 0.250 (%)	0.063 – 0.125 (%)	< 0.063 (%)	Median (Φ)	Sediment classification
1	0,085	2,791	15,018	58,079	21,865	1,186	0,261	0,715	0,55	Coarse sand
2	0,000	0,541	10,748	57,932	25,679	1,425	0,715	2,961	0,67	Coarse sand
3	0,788	7,607	22,740	20,252	9,276	2,570	1,311	35,456	0,93	Coarse sand
4	2,055	3,323	10,018	50,863	33,036	0,667	0,033	0,004	0,68	Coarse sand
5	25,203	2,222	8,003	38,113	23,908	2,310	0,123	0,119	0,38	Coarse sand
6	1,668	5,243	22,772	56,357	13,558	0,300	0,035	0,066	0,36	Coarse sand
7	0,602	1,407	16,980	55,968	24,053	0,944	0,039	0,008	0,55	Coarse sand
8	0,068	0,364	6,021	51,452	39,465	2,405	0,072	0,152	0,85	Coarse sand
9	0,924	4,619	28,793	52,745	12,639	0,203	0,024	0,053	0,30	Coarse sand
10	5,613	8,031	13,801	22,890	42,007	7,491	0,064	0,102	0,99	Coarse sand
11	0,862	3,433	8,827	31,284	48,081	7,360	0,080	0,072	1,12	Medium sand
12	0,000	0,082	0,710	2,436	8,453	25,026	17,036	46,258	3,78	Very fine sand
13	0,140	1,920	5,716	16,630	44,908	28,243	0,953	1,491	1,57	Medium sand
14	0,551	0,841	5,749	34,628	51,321	6,296	0,174	0,439	1,16	Medium sand
15	0,791	6,594	19,913	36,935	27,774	5,780	0,782	1,431	0,61	Coarse sand
16	0,228	2,160	16,849	50,832	26,773	3,073	0,063	0,021	0,61	Coarse sand
17	0,021	0,227	3,866	25,297	56,462	12,279	0,872	0,976	1,36	Medium sand
18	0,000	1,773	7,467	42,326	44,266	3,907	0,097	0,163	0,96	Coarse sand
19	0,000	0,011	1,782	4,560	12,694	6,490	3,192	71,273	>4	Mud
20	0,118	3,472	13,122	40,235	38,935	3,944	0,100	0,074	0,83	Coarse sand
21	0,000	0,000	0,532	1,135	3,490	31,914	27,563	35,365	3,47	Very fine sand
22	0,000	0,000	0,927	0,959	2,846	4,484	13,636	77,148	>4	Mud
23	0,000	0,000	1,800	3,066	6,906	5,891	5,084	77,253	>4	Mud
24	0,000	0,031	2,689	26,162	46,711	18,644	3,622	2,140	1,45	Medium sand
25	0,296	0,000	4,196	5,569	9,956	10,109	22,392	47,482	3,89	Very fine sand
26	0,000	0,000	0,112	0,739	2,518	3,783	8,551	84,298	>4	Mud
27	0,000	0,000	0,115	0,094	0,156	0,365	2,533	96,737	>4	Mud
28	0,000	0,000	0,178	0,303	0,970	7,336	23,458	67,756	>4	Mud
29	0,000	0,000	0,473	1,144	1,971	6,376	27,622	62,413	>4	Mud
30	0,000	0,000	1,510	1,256	1,853	5,031	17,701	72,649	>4	Mud
31	0,000	0,000	2,596	1,774	2,562	7,997	9,788	75,283	>4	Mud
32	0,000	0,000	0,169	0,137	0,211	0,539	3,022	95,921	>4	Mud
33	0,000	0,000	0,084	0,136	0,167	0,921	5,745	92,947	>4	Mud
34	0,000	0,000	0,011	0,075	0,097	0,194	0,926	98,698	>4	Mud
35	0,000	0,000	0,077	0,306	0,831	1,203	6,224	91,359	>4	Mud
36	0,735	0,000	6,261	7,922	13,592	11,549	10,346	49,594	3,96	Very fine sand
37	0,000	0,085	1,342	30,919	65,511	2,088	0,042	0,012	1,27	Medium sand
38	0,936	7,432	18,476	36,473	31,360	5,167	0,108	0,048	0,67	Coarse sand
39	41,899	10,187	12,080	10,923	9,597	10,574	1,341	3,398	-1,20	Gravel
40	2,241	0,000	3,452	10,753	22,971	18,553	11,291	30,739	2,57	Fine sand
41	0,000	0,000	0,322	3,122	24,535	37,613	12,885	21,523	2,59	Fine sand
42	0,142	2,263	9,290	38,186	41,984	5,842	0,853	1,440	1,00	Coarse sand
43	0,000	0,361	5,846	44,373	46,483	2,513	0,083	0,340	0,99	Coarse sand
44	0,150	0,758	5,389	32,728	53,292	6,297	0,699	0,686	1,21	Medium sand
45	0,000	0,250	6,959	46,947	42,028	3,701	0,038	0,077	0,91	Coarse sand
46	0,000	0,187	3,770	35,160	57,815	2,983	0,084	0,000	1,19	Medium sand
47	0,000	0,537	4,802	42,758	48,840	2,382	0,205	0,476	1,04	Medium sand
48	0,000	0,226	2,758	16,370	53,148	23,091	2,388	2,019	1,58	Medium sand
49	26,433	0,057	1,521	4,225	9,526	25,099	17,388	15,752	2,33	Fine sand
50	0,000	0,000	1,057	3,470	9,352	15,055	22,532	48,534	3,93	Very fine sand
51	0,000	0,000	11,465	6,901	7,073	5,270	8,014	61,277	>4	Mud
52	0,000	0,298	1,536	4,802	13,659	11,467	5,070	63,167	>4	Mud
53	0,000	0,000	3,274	2,212	2,474	2,849	6,248	82,944	>4	Mud

Site	> 4.0 (%)	2.0-4.0 (%)	1.0 – 2.0 (%)	0.5 – 1.0 (%)	0.250 – 0.500 (%)	0.125 – 0.250 (%)	0.063 – 0.125 (%)	< 0.063 (%)	Median (Φ)	Sediment classification
54	0,078	0,000	2,849	7,567	47,258	31,300	3,894	7,054	1,84	Medium sand
55	0,000	0,000	0,150	0,160	0,282	0,507	2,159	96,743	>4	Mud
56	0,000	0,000	0,021	0,021	0,094	0,187	0,947	98,730	>4	Mud
57	0,299	0,000	7,656	7,441	11,384	22,371	15,981	34,868	3,05	Very fine sand
58	0,000	0,000	0,473	0,437	0,838	4,580	17,372	76,300	>4	Mud
59	0,000	0,000	0,021	0,031	0,031	0,144	0,103	99,671	>4	Mud
60	0,000	0,000	0,089	0,022	0,111	0,089	0,255	99,435	>4	Mud
61	0,000	0,000	3,306	2,588	2,914	2,947	4,241	84,004	>4	Mud
62	1,338	0,000	7,347	6,281	13,134	21,770	9,557	40,574	3,01	Very fine sand
63	0,000	0,000	1,597	6,110	63,442	27,911	0,093	0,848	1,67	Medium sand
64	0,000	0,000	0,188	0,152	0,197	0,269	0,296	98,898	>4	Mud
65	0,000	0,000	0,061	0,040	0,081	0,101	0,111	99,607	>4	Mud
66	0,000	0,000	4,484	2,497	2,715	6,771	14,059	69,473	>4	Mud
67	0,000	0,000	0,942	2,812	8,792	51,988	14,268	21,197	2,72	Fine sand
68	0,000	0,000	0,119	0,162	0,128	0,230	0,486	98,874	>4	Mud
69	0,000	0,000	0,066	0,038	0,019	0,066	0,133	99,678	>4	Mud
70	0,000	0,000	0,039	0,029	0,107	0,136	0,194	99,496	>4	Mud
71	0,000	0,123	3,450	13,808	45,163	35,514	0,881	1,060	1,72	Medium sand
72	0,000	0,000	0,063	0,048	0,143	0,158	0,182	99,406	>4	Mud
73	0,000	0,000	0,225	0,135	0,144	0,351	1,755	97,390	>4	Mud
74	0,000	0,000	0,047	0,039	0,055	0,109	0,140	99,611	>4	Mud
75	0,000	0,000	0,038	0,057	0,095	0,293	4,647	94,870	>4	Mud
76	0,000	0,000	2,773	10,463	15,549	24,615	12,898	33,702	2,86	Fine sand
77	0,000	0,000	0,093	0,072	0,155	0,228	0,197	99,255	>4	Mud
78	0,000	0,000	0,313	0,091	0,101	0,182	0,071	99,242	>4	Mud
79	0,000	0,000	0,319	0,258	0,540	0,491	0,233	98,158	>4	Mud
80	0,000	0,000	0,195	0,080	0,126	0,207	0,138	99,253	>4	Mud
81	0,000	0,000	0,604	0,466	0,377	0,390	0,277	97,886	>4	Mud
82	0,000	0,000	0,485	0,459	1,161	0,957	0,536	96,403	>4	Mud
83	0,000	0,000	0,283	1,773	32,623	49,066	12,487	3,767	2,31	Fine sand
84	0,000	0,000	0,032	0,040	0,072	0,184	1,161	98,511	>4	Mud
85	0,000	0,000	0,563	2,777	5,986	10,970	21,610	58,094	>4	Mud
86	0,124	0,253	1,481	6,258	29,141	28,914	13,565	20,264	2,44	Fine sand
87	0,000	0,000	0,035	0,206	1,304	18,709	46,219	33,527	3,64	Very fine sand
88	0,000	0,000	0,040	0,020	0,050	0,121	0,353	99,415	>4	Mud
89	0,000	0,000	0,132	0,033	0,041	0,058	0,083	99,653	>4	Mud
90	0,000	0,000	0,042	0,050	0,042	0,109	0,092	99,665	>4	Mud
91	0,000	0,000	0,541	0,419	0,878	0,946	0,284	96,932	>4	Mud
92	0,000	0,000	0,123	0,101	0,145	0,123	0,157	99,351	>4	Mud
93	0,000	0,000	15,380	6,214	3,448	2,126	1,486	71,346	>4	Mud
94	0,000	0,000	0,131	0,076	0,458	0,556	0,392	98,387	>4	Mud
95	0,000	0,000	3,968	2,663	2,783	3,408	0,519	86,660	>4	Mud
96	0,000	0,000	0,248	0,106	0,259	0,460	0,566	98,361	>4	Mud
97	0,000	0,000	0,068	0,102	0,094	0,171	0,179	99,386	>4	Mud
98	0,000	0,000	0,114	0,159	0,558	0,911	0,717	97,540	>4	Mud
99	0,000	0,000	0,145	0,123	0,646	0,924	0,991	97,171	>4	Mud
100	0,000	0,000	0,034	0,034	0,170	0,295	0,193	99,274	>4	Mud
101	0,000	0,000	0,155	0,165	0,569	1,116	1,065	96,930	>4	Mud
102	0,000	0,000	0,050	0,025	0,150	0,383	0,524	98,868	>4	Mud
103	0,000	0,000	0,039	0,023	0,062	0,163	0,854	98,859	>4	Mud
104	0,000	0,000	0,018	0,024	0,066	0,113	1,706	98,073	>4	Mud
105	0,000	0,000	0,331	0,115	0,065	0,058	0,425	99,007	>4	Mud
106	0,000	0,000	0,206	0,165	0,399	0,261	0,124	98,844	>4	Mud
107	0,574	0,901	7,979	39,419	45,091	5,776	0,088	0,172	1,03	Medium sand

Table 10. Environmental data from Lagoon of Óbidos: Biogenic fraction (expressed as percent of total sediment dry weight); TVS= Total volatile Solids; RP= Redox Potential; T= Temperature.

Site	Biogenic fraction (%)	TVS (%)	RP (mV)	T (ºC)	Algae abundance	Molluscs Total abundance (0.05 m^2)
1	0.48	0.47	147	13.5	Low	333
2	0.19	0.67	201	15.5	Low	236
3	4.82	4.83	99	17.5	High	475
4	0.54	0.54	295	14.5	Absence	11
5	0.25	0.04	334	14.0	Low	88
6	0.12	0.09	333	15.0	Absence	3
7	0.09	0.08	363	15.0	Absence	1
8	0.05	0.32	351	16.0	Absence	127
9	0.17	0.21	358	15.5	Absence	4
10	4.55	0.24	370	15.0	Low	13
11	0.11	0.46	377	14.5	Low	7
12	2.56	6.25	-198	17.0	High	36
13	1.93	0.40	152	15.0	High	177
14	1.59	0.48	189	15.5	Medium	361
15	2.62	0.50	247	16.0	High	58
16	1.94	0.28	288	15.0	Absence	15
17	6.06	0.43	228	18.0	Absence	113
18	3.05	0.19	308	16.0	Absence	162
19	1.99	4.97	48	16.0	Absence	162
20	5.60	1.37	295	17.0	Absence	11
21	1.13	3.34	-6	17.0	High	332
22	2.61	6.18	-116	18.0	High	90
23	7.08	7.08	-114	18.0	High	203
24	1.88	0.61	149	18.0	High	36
25	9.60	3.31	104	17.5	High	109
26	0.85	6.80	-66	18.0	Medium	226
27	0.09	7.39	36	17.5	Absence	27
28	0.10	5.73	47	18.0	Absence	34
29	1.30	4.93	-84	18.0	Absence	56
30	5.11	2.87	88	18.5	Medium	20
31	10.02	4.18	20	18.0	High	14
32	0.90	5.90	-3	18.5	High	239
33	0.67	6.36	34	18.5	Absence	15
34	0.00	6.34	27	18.0	Absence	28
35	0.08	6.65	4	18.0	Low	220
36	10.99	5.73	56	20.0	High	51
37	0.04	0.61	350	15.0	Absence	0
38	0.17	0.20	352	15.5	Absence	2
39	4.05	1.12	319	15.0	High	39
40	3.05	3.08	47	15.0	Medium	190
41	1.13	2.10	97	16.5	Medium	95
42	1.91	0.30	299	16.5	Low	32
43	0.80	0.33	318	16.5	High	667
44	1.87	0.31	338	16.0	Medium	377
45	0.50	0.06	328	15.5	Absence	1
46	0.54	0.16	264	15.0	Low	30
47	4.32	0.30	339	15.5	Medium	552
48	1.20	0.67	344	15.5	Low	17
49	4.15	1.86	136	17.0	High	3
50	18.73	6.51	89	17.5	High	51
51	37.95	7.81	89	18.0	High	5
52	4.56	14.77	74	18.0	High	35
53	22.72	10.99	-44	18.5	High	36

Site	Biogenic fraction (%)	TVS (%)	RP (mV)	T (ºC)	Algae abundance	Molluscs Total abundance (0.05 m^2)
54	2.78	1.12	282	18.0	High	144
55	2.86	10.15	39	18.5	Absence	18
56	0.01	11.05	28	18.5	Absence	30
57	7.97	4.10	56	18.5	High	43
58	2.10	10.07	-14	18.0	High	26
59	0.03	10.88	4	19.0	Absence	55
60	0.98	11.62	24	19.0	Absence	57
61	23.75	9.46	27	18.0	High	121
62	18.13	6.19	40	18.5	High	54
63	2.49	0.59	281	19.0	Absence	1828
64	4.30	11.41	43	18.5	Absence	86
65	1.52	10.59	38	19.0	Low	6
66	14.51	7.17	41	19.5	Medium	41
67	1.50	3.16	77	16.0	Absence	139
68	0.06	9.85	55	16.5	Medium	47
69	0.10	9.74	16	19.0	High	62
70	0.03	9.48	36	19.0	Absence	17
71	3.22	0.61	251	19.0	Medium	244
72	3.27	8.75	20	19.5	Absence	29
73	2.37	9.13	16	19.5	Medium	62
74	0.08	8.93	44	19.5	Absence	98
75	0.26	7.35	42	20.0	Absence	55
76	0.26	3.94	68	20.0	Absence	33
77	0.10	11.75	-81	19.5	High	144
78	0.34	11.39	10	19.5	High	274
79	0.17	11.17	-7	20.0	High	161
80	0.06	9.99	-80	20.0	High	259
81	1.22	11.80	-150	20.0	High	66
82	0.72	10.43	-64	22.0	High	423
83	0.71	0.76	233	20.0	Absence	195
84	1.19	7.94	77	19.5	Absence	33
85	1.89	4.86	114	20.0	Absence	9
86	0.18	1.91	54	20.0	Absence	16
87	0.04	2.58	49	20.0	Absence	62
88	0.31	9.08	11	20.0	Medium	54
89	2.68	8.25	40	20.0	Medium	245
90	0.67	8.17	9	20.0	Absence	546
91	0.48	12.60	-109	20.5	High	411
92	0.13	10.03	2	19.0	Absence	290
93	55.67	6.83	17	22.0	Low	95
94	0.28	11.41	98	20.0	Absence	459
95	16.80	13.54	-8	21	Absence	177
96	1.97	11.62	27	21.5	Low	469
97	0.02	10.91	-138	21.0	High	2272
98	0.19	11.82	-158	22.0	High m	966
99	0.17	13.48	-154	21.5	High	1202
100	0.03	11.13	-150	21.5	High	616
101	1.56	10.99	57	20.0	Absence	81
102	1.16	10.16	37	19.5	Absence	60
103	0.01	9.56	31	19.5	Absence	14
104	0.00	7.53	44	20.0	Absence	24
105	0.81	10.98	46	20.5	Medium	366
106	0.14	15.43	-61	20.0	High	333
107	1.20	0.33	352	17.0	Low	29

The spatial distribution of the sediment types reveals a clear longitudinal pattern. Closer to the entrance the seabed is composed of coarse sediments (gravel and coarse sand). This bottom type is a result of the proximity to the sea and, consequently, the higher values of current velocity at the mouth of the lagoon. Towards the inner part of the lagoon, both navigation channels are mainly characterised by medium sand. The central body of the lagoon and the Barrosa and Bom Sucesso arms are characterised by finer sediments, mainly mud with a very high percentage of silt and clay (cf. Figure 15 and Table 9).

Figure 16 displays the three acoustic classes jointly with the sediment types and reveal that there is no clear relationship between the two patterns.

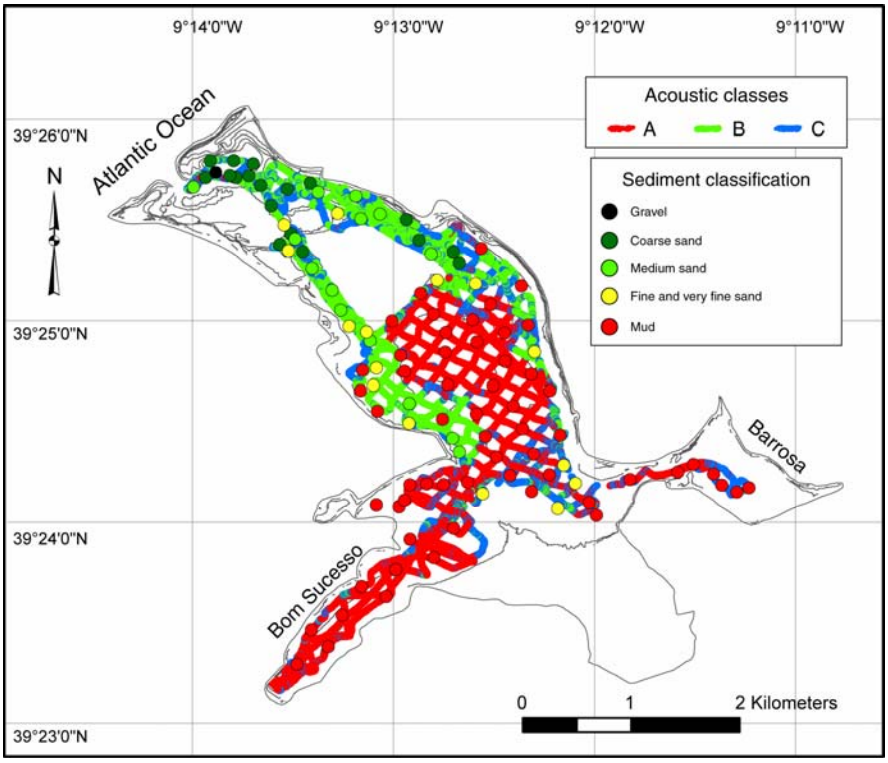


Figure 16. Lagoon of Óbidos. GIS representation of the three acoustic classes jointly displayed with the sediment types.

However, by dropping the acoustic solution down to two classes (the two first acoustic classes) it is possible to observe a closer relationship between the acoustic classes (A and B) and the sediment types (Figure 17).

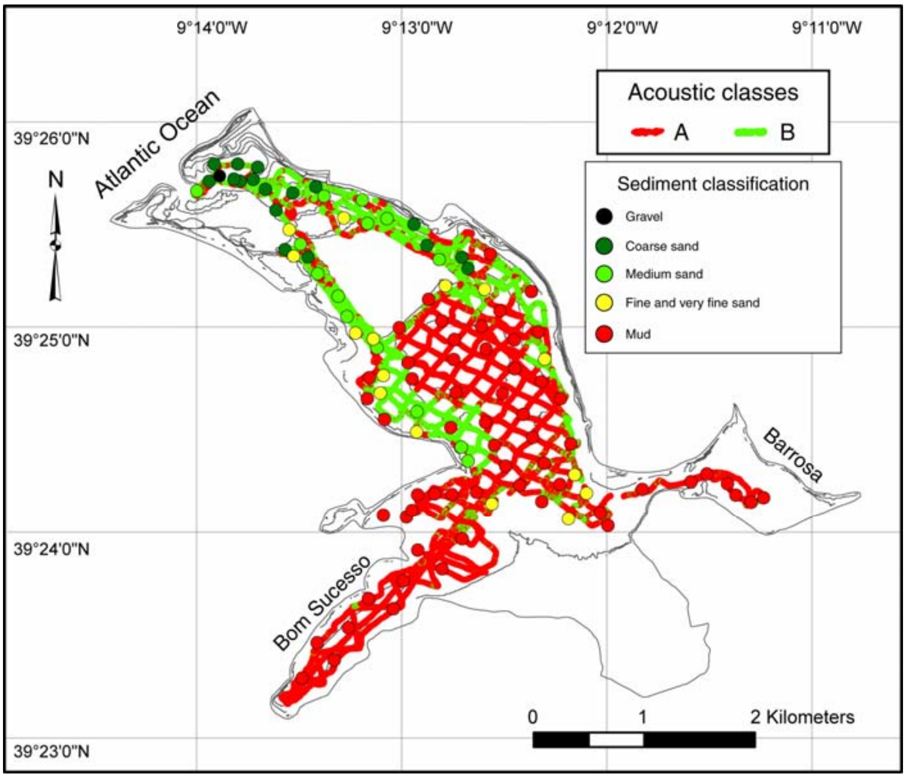


Figure 17. Lagoon of Óbidos. GIS representation of the two first acoustic classes (first split level) jointly displayed with the sediment types.

The acoustic class A presents a close relationship with the finer sediments (mainly mud) whereas the acoustic class B corresponds to the coarser sediments (fine, medium and coarse sands). Although no close correspondence could be encountered between the acoustic classes and the various bottom types, the acoustic diversity essentially separates the muddier from the sandier bottoms.

The acoustic pattern was also compared to the distribution of algae and molluscs abundance classes, presented in Figures 18 and 19 (cf. Table 10). Algae tend to be more abundant in areas closer to the lagoon margin and again no detailed relationship could be found between any of these two descriptors and the acoustic diversity.

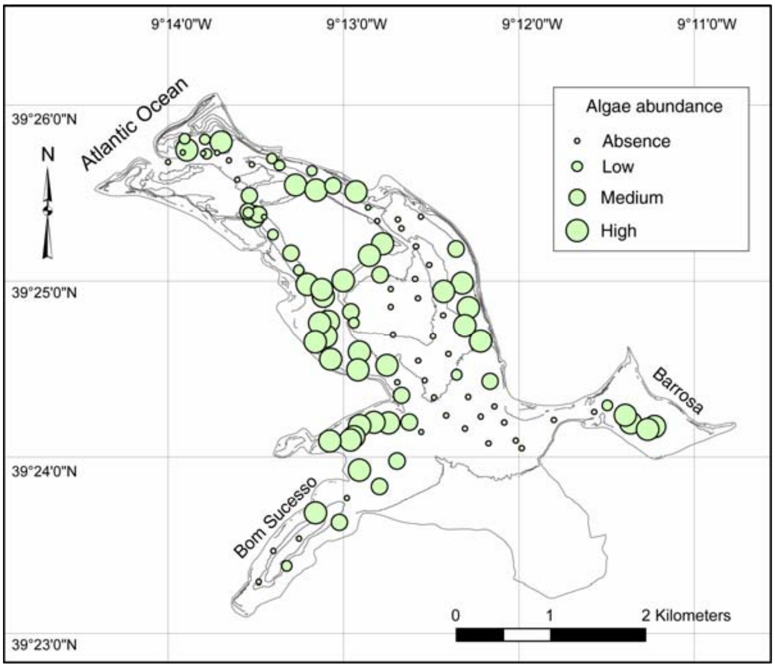


Figure 18. Lagoon of Óbidos. GIS representation of algae abundance classes.

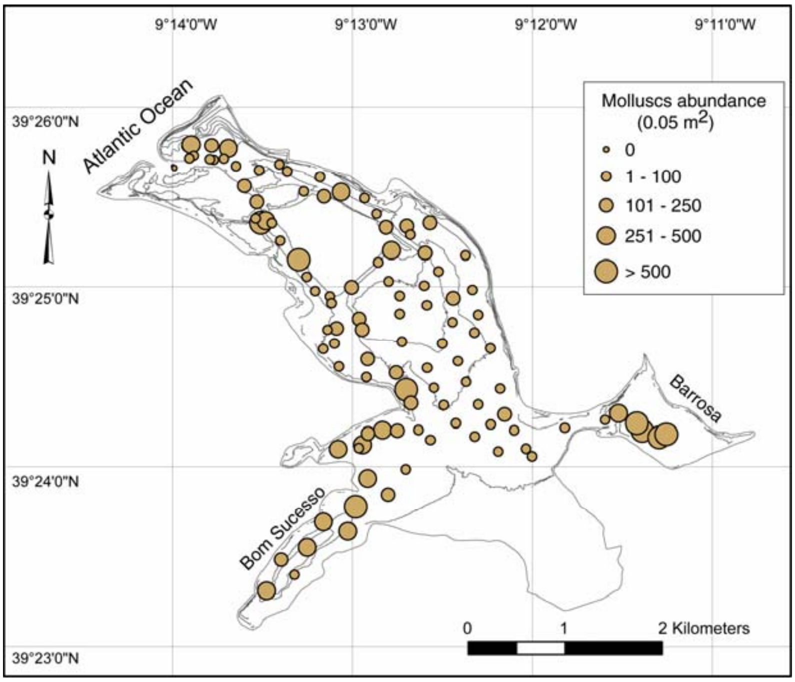


Figure 19. Lagoon of Óbidos. GIS representation of mollusc abundance classes (specimens per 0.05 m^2).

3.2 Entrance channel of Ria de Aveiro and near shore shelf

3.2.1 Acoustic pattern

The results from the acoustic classification, obtained with the manual cluster analysis, are shown in Table 11.

Table 11. Entrance channel of Ria de Aveiro and near shore shelf. Acoustic classification statistics obtained by manual clustering up to the seventh split (eight classes). Total Score = sum of the scores of the individual classes; CPI = cluster performance index; CPI rate = [CPI (n) – CPI (n-1)] / CPI (n-1), where n is the split number.

Split	Number of classes	Total Score	CPI	CPI rate
0	1	358771.97	_	_
1	2	122082.28	1.97	_
2	3	20486.18	10.23	4.19
3	4	13782.09	17.25	0.69
4	5	11793.06	31.55	0.83
5	6	11988.08	56.37	0.79
6	7	10504.74	80.69	0.43
7	8	9849.21	124.62	0.54

According to the CPI rate, the optimal classification corresponds to the second split (three acoustic classes), where it is maximum. Figure 20a shows the diminishing of the Total Score as splitting occurs. Total Score decreases abruptly up to the second split (three acoustic classes) and tends to level at the third split (four acoustic classes), after which the reduction in Total Score values shown in Table 11 becomes imperceptible in the graph of Figure 20a. Thus, optimal classification may consider three or four acoustic classes, corresponding to the second and the third split level respectively.

This data set was also submitted to auto-cluster analysis, only available in the most recent version of QTC IMPACT (QTC IMPACT, 2004). Figure 20b shows how Total Score diminishes with the increasing number of acoustic classes, in auto-cluster analysis.

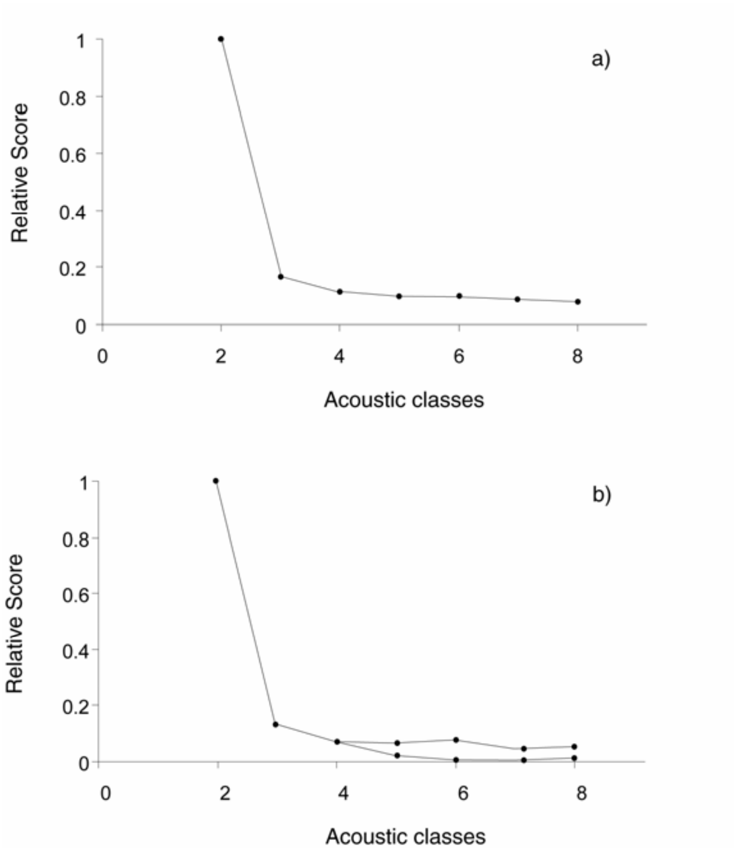


Figure 20. Entrance channel of Ria de Aveiro and near shore shelf. Relative score, expressed as standardized values for the Total Score obtained with two acoustic classes. a) Manual clustering; b) Auto-cluster, showing the maximum and the minimum iteration score values, only perceptible as Total Score tends to level.

The simulated annealing K-means procedure in auto-cluster results in a different Total Score each time the annealing procedures runs (QTC IMPACT, 2004). Up to four acoustic classes, this variability is imperceptible but becomes obvious from five acoustic classes onwards, as shown in Figure 20b, where the lines are draw through the minimum and the maximum score value for each number of acoustic classes. Although the absolute minimum score value was obtained with six classes (cf. Figure 20b), the procedure shows high variability within each class number, as Total Score starts to level out, i. e. after four acoustic classes. Up to four acoustic classes, the score iterations within each class were very similar, indicating that the possible alternative results were very close to each other. Beyond five acoustic classes, inclusive, the score iteration values have large amplitude changes, indicating a high uncertainty to obtain a minimum score for those classes. Although the absolute minimum was obtained with six classes, the auto-cluster results also suggest an optimal classification with four acoustic classes.

The geographic distribution of three and four acoustic classes obtained with manual cluster and four and five acoustic classes obtained with auto-cluster, are shown in Figures 21 and 22, respectively.

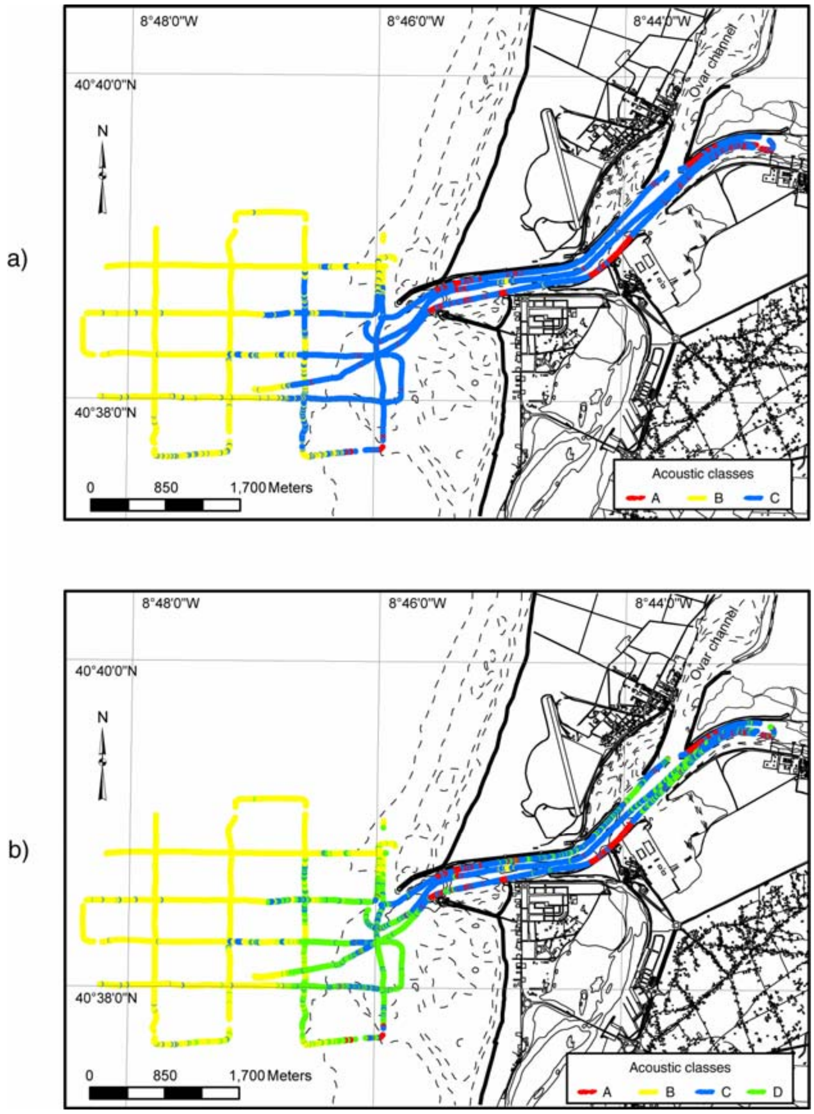


Figure 21. Entrance channel of Ria de Aveiro and near shore shelf. GIS representation of the acoustic pattern considering three (a) and four (b) acoustic classes obtained with manual clustering of the data.

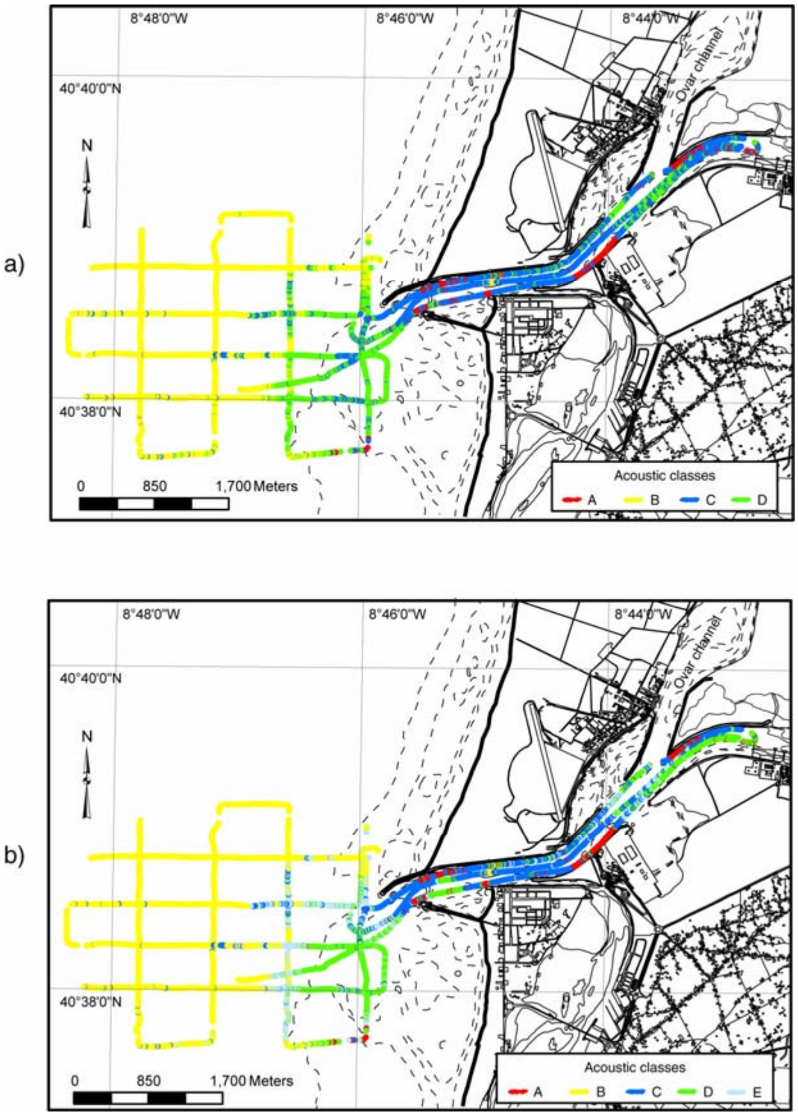


Figure 22 Entrance channel of Ria de Aveiro and near shore shelf. GIS representation of the acoustic pattern considering four (a) and five (b) acoustic classes obtained with auto-clustering of the data.

The quality of the acoustic classification is demonstrated by the agreement between the intercepting survey lines. The spatial pattern obtained with three and four classes is very clear, whereas the fifth class in the auto-cluster introduces noise and a lesser clear final pattern. This is in agreement with the less clear score results of five acoustic classes in auto-cluster (cf. Figure 20b). In this way, the solution of four acoustic classes (obtained both with manual and auto-clustering) was selected as the best acoustic result for this area.

3.2.2 Ground-truth

Concerning the sedimentary data, Table 12 shows the results of the sediment grain-size analysis for each site, the median value and the sediment classification.

Apart from the hard bottom areas detected close to the artificial margins of the navigation channel (sites 13, 14 and 17), the soft sediments showed three major sediment groups in the study area, as shown in the classification and ordination diagrams presented in Figure 23.

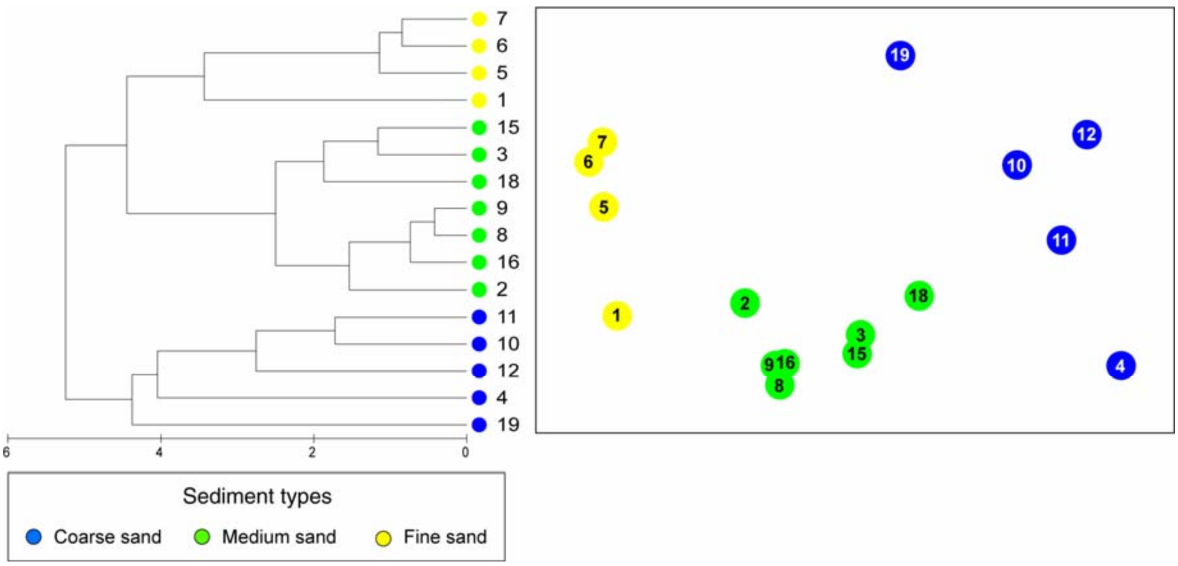


Figure 23. Entrance channel of Ria de Aveiro and near shore shelf. Classification and ordination diagrams issued from the analysis of the sedimentary data.

The three sediment groups correspond mainly to coarse, medium and fine sand, according to the sediment classification criteria considered, but also included one site with sandy gravel (site 12) and another with very fine sand, although in this case the median value is just slightly above 3.00 Φ (site 7, cf. Table 12). All soft sediments presented very low silt and clay content (<5%), as would be expected in an area where tidal currents daily exceed 1m/s and often reach 3m/s (Dias et al., 2000).

Table 12. Superficial sediment grain-size analysis from the entrance channel of Ria de Aveiro and near shore shelf. Grain-size classes (in mm) values are expressed as percent of total sediment dry weight, median value in phi units (Φ) and sediment classification according to Table 7, except for site 12 classified as sandy gravel and sites 13, 14 and 17 corresponding to hard bottom.

Site	> 4.0 (%)	2.0-4.0 (%)	1.0 – 2.0 (%)	0.5 – 1.0 (%)	0.250 – 0.500 (%)	0.125 – 0.250 (%)	0.063 – 0.125 (%)	< 0.063 (%)	Median (Φ)	Sediment classification
1	0.04	0.05	0.19	1.57	10.06	84.57	3.52	0.02	2.45	Fine sand
2	0.00	0.03	0.20	2.99	56.73	39.14	0.78	0.12	1.82	Medium sand
3	0.59	2.02	6.98	15.80	66.58	7.62	0.22	0.18	1.37	Medium sand
4	11.09	13.27	24.33	29.43	19.01	2.67	0.19	0.01	0.04	Coarse sand
5	0.01	0.00	0.09	0.38	3.46	57.37	37.12	1.56	2.80	Fine sand
6	0.03	0.04	0.07	0.42	3.79	51.56	41.92	2.17	2.89	Fine sand
7	0.01	0.07	0.11	0.77	13.34	35.01	48.51	2.17	3.01	Very fine sand
8	0.00	0.02	0.07	1.95	86.82	10.78	0.23	0.14	1.55	Medium sand
9	0.00	0.00	0.14	2.18	82.60	14.78	0.24	0.06	1.58	Medium sand
10	27.59	10.36	5.57	16.29	37.21	2.74	0.20	0.05	0.40	Coarse sand
11	16.76	14.26	13.93	18.68	33.77	2.41	0.13	0.06	0.27	Coarse sand
12	40.15	12.43	10.18	10.41	25.44	1.15	0.07	0.18	-1.21	Sandy gravel
15	2.91	0.78	1.02	20.26	68.77	6.06	0.17	0.03	1.36	Medium sand
16	0.00	0.00	0.14	1.74	87.31	10.64	0.15	0.02	1.55	Medium sand
18	6.45	8.86	10.17	20.10	46.13	7.65	0.30	0.36	1.10	Medium sand
19	23.80	15.06	7.31	6.19	24.84	16.55	2.70	3.54	0.62	Coarse sand

The three main soft sediment types and the hard bottom, obtained for the studied area, were spatially represented using the GIS software (Figure 24).

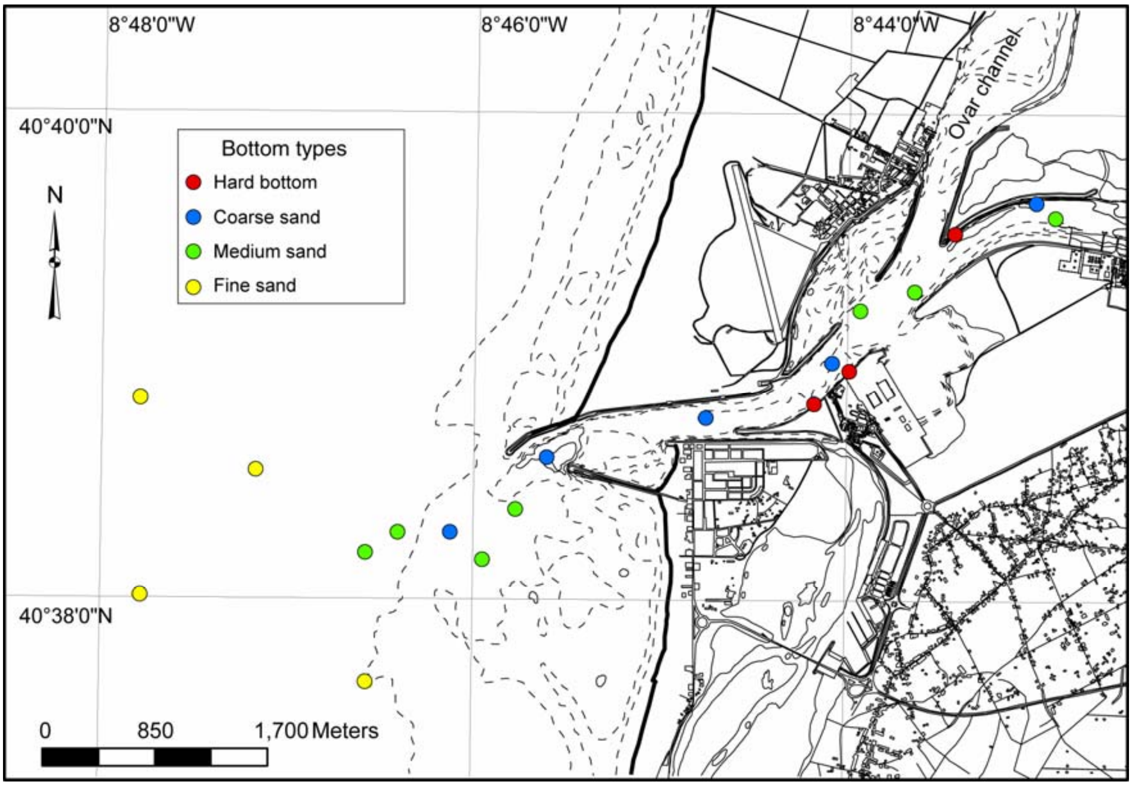


Figure 24. Entrance channel of Ria de Aveiro and near shore shelf. GIS representation of the four sediment types identified.

The analysis of the relationship between the acoustic and the sedimentary data is presented in Figure 25, where closer correspondences are identified between the two data sets. Class A, located closer to the margins of the navigation channel, corresponds to a rocky bottom, related with the artificial margins. Class B, located on the coastal shelf, corresponds to clean fine sand. Class C is the predominant class in the navigation channel and corresponds to the higher energy area composed of coarse sand. The coarse sands in the navigation channel are only interrupted at the interception between this channel and the Northern Ovar channel. Finally, class D corresponds to clean medium sand. This acoustic class is mainly located near the mouth of the entrance channel and makes the transition from the coarse sand from the navigation channel to the fine sand of the near shore shelf. The acoustic solution with only three acoustic classes would have completely omitted the differentiation between medium and coarse sand (cf. Figures 21a, 21b and 23), whereas the solution with five acoustic classes suggests a detailed separation within the medium sands but resulting in a less clear spatial pattern, unexplainable by the currently available ground-truth data (cf. Figures 22a, 22b and 23).

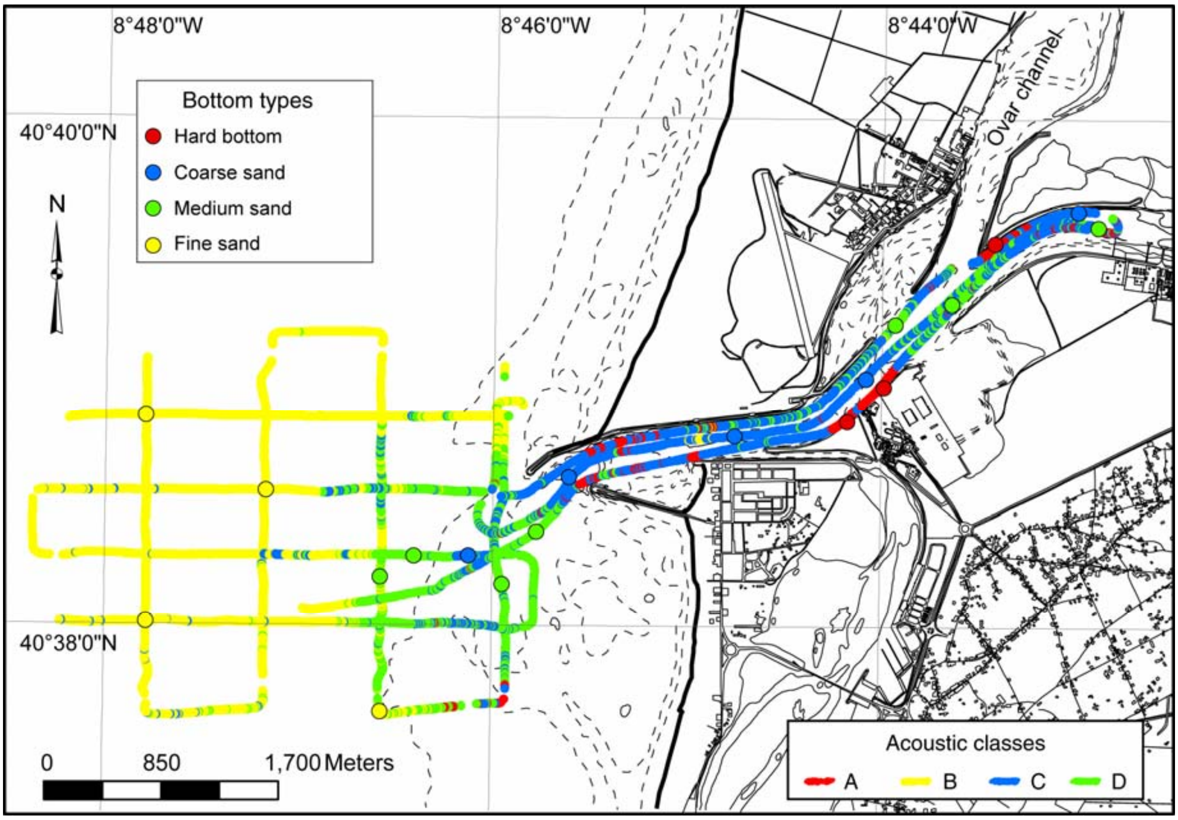


Figure 25. Entrance channel of Ria de Aveiro and near shore shelf. Final acoustic diversity solution with a GIS representation of the four acoustic classes jointly displayed with the sediment types.

3.3 Near shore shelf off Aveiro

3.3.1 Acoustic pattern

The results of the acoustic classification by manual clustering up to the fourth split are shown in Table 13. The optimal solution was obtained at the second split, when the Total Score begins to stabilize (Figure 26) and the CPI rate attains its maximum value. At this split level, three acoustic classes were identified and named A, B and C.

Table 13. Near shore shelf off Aveiro. Acoustic classification statistics obtained by manual clustering up to the fourth split (five classes). Total Score = sum of the scores of the individual classes; CPI = cluster performance index; CPI rate = [CPI (n) – CPI (n-1)] / CPI (n-1), where n is the split number.

Split	Number of classes	Total Score	CPI	CPI rate
0	1	93878627.97	_	_
1	2	6590391.00	10.30	_
2	3	3873367.48	26.78	1.60
3	4	3341488.47	58.14	1.17
4	5	3020399.58	115.73	0.99

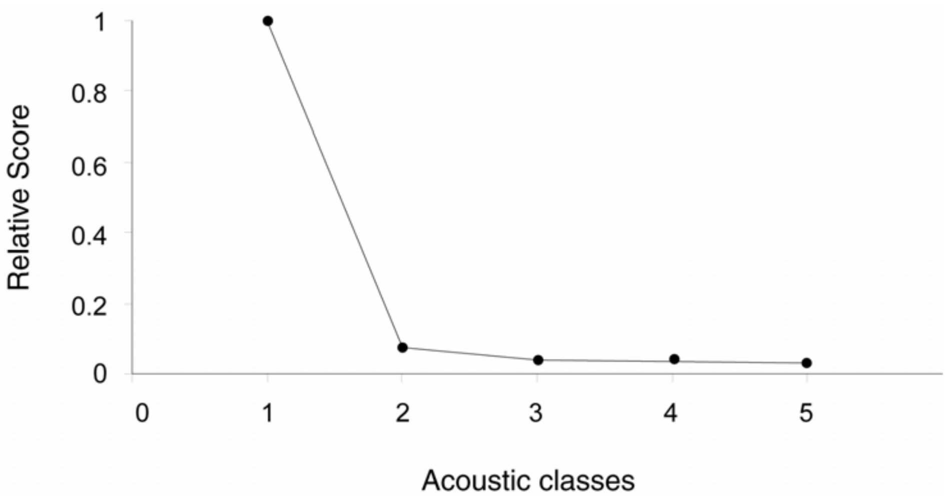


Figure 26. Near shore shelf off Aveiro. Relative score, expressed as standardized values for the Total Score obtained with one acoustic class.

The geographical distribution of the three acoustic classes identified is presented in Figure 27.

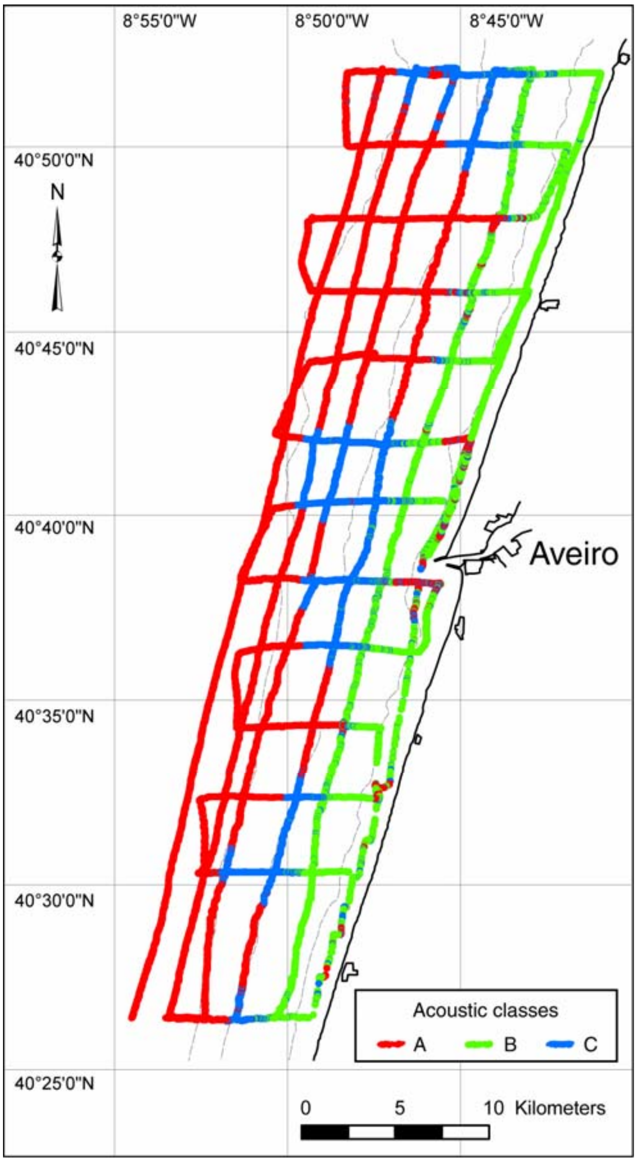


Figure 27. Near shore shelf off Aveiro. GIS representation of the acoustic pattern.

The three acoustic classes obtained for the studied area exhibit a very clear inshore-offshore pattern, neither related to the bathymetry contours, nor parallel to the shoreline. This is particularly clear with this data set, emphasizing the independency of QTC VIEW from the survey depth.

The stability of the acoustic classification is supported by the agreement of the acoustic classification where survey lines intersect.

3.3.2 Ground-truth

Concerning the sedimentary data, Table 14 presents the results of the sediment grain-size analysis for each site, including the median and the sediment classification, according to Table 7.

The ordination analysis relative to the sediment grain-size data is presented in Figure 28, to which the sediment classification was superimposed.

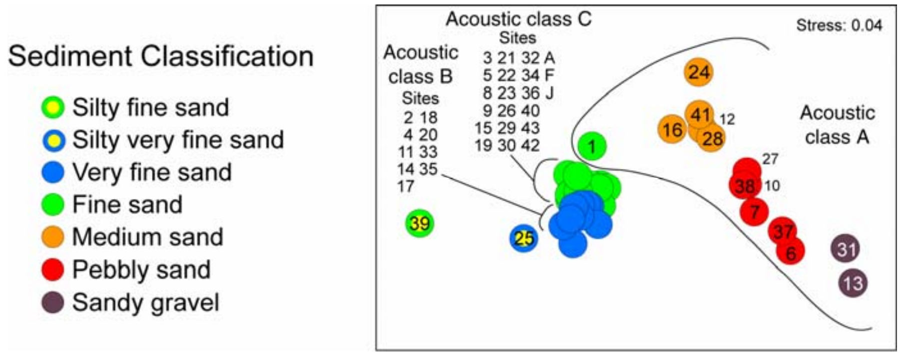


Figure 28. Near shore shelf off Aveiro. Sediment classification superimposed on a non-metric multidimensional scaling of the samples grain-size data. Also shown is the delineation of the acoustic classes A, B and C.

Table 14. Superficial sediment grain-size analysis from near shore shelf off Aveiro. Grain-size classes (in mm) values are expressed as percent of total sediment dry weight, median value in phi units (Φ) and sediment classification according to Table 7.

Site	> 2.0 (%)	1.0 – 2.0 (%)	0.5 – 1.0 (%)	0.250 – 0.500 (%)	0.125 – 0.250 (%)	0.063 – 0.125 (%)	< 0.063 (%)	Median (Φ)	Sediment classification
1	0.10	0.26	2.17	14.01	69.41	13.09	0.95	2.50	Fine sand
2	0.01	0.09	0.83	6.24	42.02	49.26	1.55	3.02	Very fine sand
3	0.06	0.10	0.47	1.99	48.41	47.82	1.15	2.99	Fine sand
4	0.13	0.05	0.60	3.81	45.14	48.76	1.51	3.01	Very fine sand
5	0.51	0.59	3.27	11.38	49.64	33.46	1.15	2.73	Fine sand
6	7.98	29.66	46.76	14.24	0.93	0.05	0.37	0.29	Pebbly sand
7	9.94	20.54	35.66	31.65	1.64	0.13	0.44	0.55	Pebbly sand
8	0.18	0.09	2.40	17.64	42.78	35.74	1.17	2.71	Fine sand
9	0.02	0.18	3.03	9.88	51.54	33.50	1.85	2.78	Fine sand
10	5.38	13.88	45.76	32.90	1.76	0.04	0.28	0.70	Pebbly sand
11	0.09	0.13	2.16	9.95	27.56	58.47	1.63	3.12	Very fine sand

Site	> 2.0 (%)	1.0 – 2.0 (%)	0.5 – 1.0 (%)	0.250 – 0.500 (%)	0.125 – 0.250 (%)	0.063 – 0.125 (%)	< 0.063 (%)	Median (Φ)	Sediment classification
12	1.41	0.69	26.75	58.24	7.94	4.75	0.22	1.37	Medium sand
13	26.99	29.94	34.14	8.13	0.47	0.03	0.31	-0.21	Sandy gravel
14	0.00	0.03	0.37	0.73	47.40	49.72	1.74	3.02	Very fine sand
15	0.16	0.12	1.57	6.20	42.07	48.41	1.48	2.99	Fine sand
16	0.35	0.84	10.57	60.04	19.26	8.41	0.53	1.70	Medium sand
17	0.01	0.07	0.82	1.83	24.65	69.90	2.72	3.25	Very fine sand
18	0.00	0.03	0.23	0.81	39.97	56.99	1.97	3.10	Very fine sand
19	1.47	1.17	0.85	4.12	44.07	46.73	1.58	2.98	Fine sand
20	0.04	0.02	0.06	0.64	36.32	59.61	3.30	3.19	Very fine sand
21	0.04	0.06	0.21	1.46	59.46	36.73	2.04	2.90	Fine sand
22	0.28	0.17	1.17	4.39	50.65	40.76	2.58	2.90	Fine sand
23	0.08	0.09	0.84	6.01	53.70	36.58	2.70	2.81	Fine sand
24	0.01	0.14	9.26	84.10	5.90	0.14	0.45	1.48	Medium sand
25	0.03	0.04	0.08	0.61	30.59	63.33	5.34	3.25	Silty very fine sand
26	0.03	0.08	0.42	2.29	60.13	35.08	1.98	2.85	Fine sand
27	2.38	11.47	51.09	31.85	2.91	0.03	0.27	0.75	Coarse sand
28	0.53	2.87	33.81	53.45	8.14	0.67	0.52	1.20	Medium sand
29	0.02	0.03	1.03	8.87	47.65	40.10	2.29	2.88	Fine sand
30	0.08	0.11	0.74	5.63	47.37	43.04	3.03	2.95	Fine sand
31	29.19	22.21	25.25	21.83	1.31	0.03	0.18	-0.05	Sandy gravel
32	0.19	0.11	1.17	13.04	35.52	48.42	1.55	2.99	Fine sand
33	0.03	0.01	0.13	0.97	45.37	51.06	2.43	3.05	Very fine sand
34	0.06	0.04	0.16	0.51	49.60	47.48	2.16	3.00	Fine sand
35	0.17	0.04	0.18	0.72	39.21	56.92	2.77	3.11	Very fine sand
36	0.11	0.07	0.13	0.95	55.51	40.80	2.44	2.95	Fine sand
37	18.79	21.42	33.33	23.54	2.63	0.04	0.25	0.29	Pebbly sand
38	5.75	12.78	44.25	34.81	1.80	0.14	0.48	0.74	Pebbly sand
39	0.20	0.07	0.17	1.94	54.47	33.74	9.41	2.94	Silty fine sand
40	0.10	0.07	0.48	3.82	48.22	45.34	1.97	2.99	Fine sand
41	0.07	0.58	23.52	65.34	9.80	0.12	0.57	1.35	Medium sand
42	0.11	0.11	1.28	17.62	43.73	34.98	2.17	2.73	Fine sand
43	0.06	0.21	0.53	2.06	65.37	29.44	2.33	2.80	Fine sand
A	0.02	0.07	1.17	4.53	52.83	39.28	2.16	2.86	Fine sand
F	0.05	0.16	0.22	0.81	54.14	42.18	2.61	2.95	Fine sand
J	0.04	0.05	0.36	3.01	62.14	32.95	1.53	2.80	Fine sand

The samples distribution in the ordination diagram defines a gradual sediment succession, from the very coarse to the very fine sands. The same gradual pattern can be seen in Figure 29, where sediment classification for each sampling site is spatially represented over the studied area.

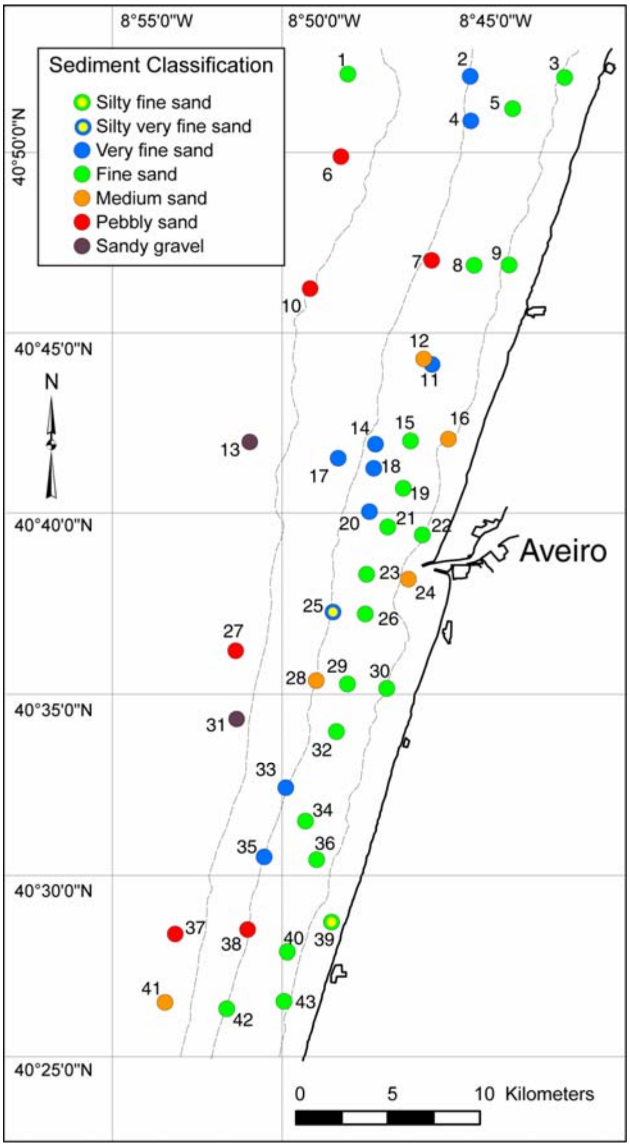


Figure 29. Near shore shelf off Aveiro. GIS representation of the sediment types identified.

The survey area is characterised by a variety of sands, ranging from very fine to very coarse with more than 25% gravel content, all with very low fines content (cf. Table 14). The highest values of fines were recorded at sites 25 and 39, with silt and clay fractions between 5% and 10% of the total sediment dry weight (cf. Table 14). No obvious bottom features were detected, such as emergent biogenic structures, algal mats or bedrock. The whole survey area may be described as a relatively monotonous sublittoral sandy plain with a gentle slope. At shallower depths, the sand tends to be finer, with the exception of a few sites closer to the shore or at the entrance channel of Ria de Aveiro, where medium sand occurred (sites 16 and 24, cf. Figure 29). The transition from fine sand to medium sand, at the entrance channel of Ria de Aveiro was detailed in the previous study area presentation. Coarser sediments (pebbly sand and sandy gravel) occurred offshore, generally beyond 20 meters depth. Apparently, the separation between the finer and the coarser sediments is quite sharp, as few sites with medium sand were detected offshore (sites 12, 28 and 41, cf. Figure 29).

Regarding the biological data, Figure 30 presents the correspondence analysis diagram resulting from the ordination analysis. Tables 15 and 16 present, respectively, the comparison of the two biological assemblages, defined by correspondence analysis, and the benthic macrofauna succession from the offshore gravely sand community to the inshore fine/very fine sand community.

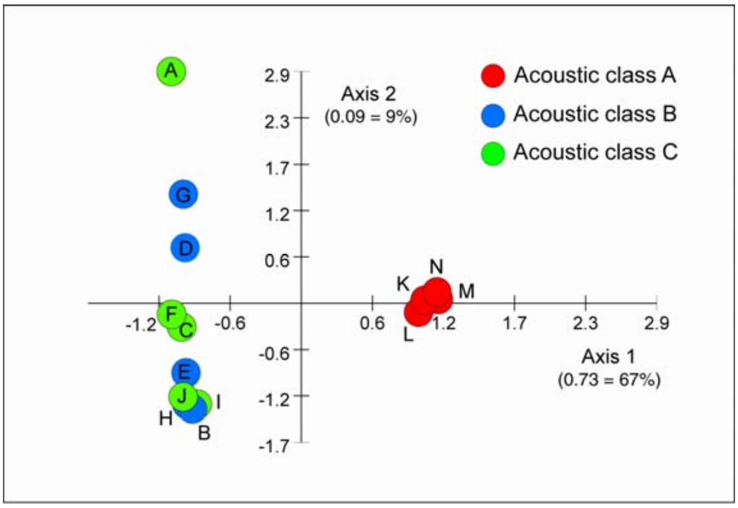


Figure 30. Near shore shelf off Aveiro. Ordination diagram of the biological data, representing the distribution of the samples on plane 1-2 of a correspondence analysis. In this diagram, the samples are coloured in agreement with their position within the three acoustic classes.

Table 15. Comparison of the two biological assemblages obtained for the near shore shelf off Aveiro, as defined by correspondence analysis.

	Gravely sand community (Offshore)		**Fine/very fine sand community (Inshore)**	
Sampling sites	K, L, M, N		A, B, C, D, E, F, G, H, I, J	
Acoustic classes	Class A		Classes B and C	
Total number of species sampled	173			
Total species richness (S)	136		72	
Mean species richness ($S/0.1m^2$)	45.1		20.9	
Species present in more than 50% of the sites	45		32	
Species exclusive to each community	101		37	
Species common to both communities	35 (=173-(101+37))			
Total abundance (A)	11318		4191	
Mean abundance ($A/0.1m^2$)	943.2		139.7	
Abundance of the species common to both communities	7537 (49% of the total)			
Abundance of the species exclusive to each community	6951 (61%)		1021 (24%)	
Dominant species, representing more than 1% of each community mean abundance ($A/0.1m^2$). Species shown in bold are common to both lists.	Nematodes	232.2	***Mediomastus fragilis***	51.0
	Polygordius appendiculatus	205.4	*Magelona johnstoni*	32.2
	Pisione remota	94.3	*Donax cf.semistriatus*	6.4
	Aonides oxycephala	73.4	*Owenia fusiformis*	5.7
	Protodorvillea kefersteini	57.9	***Spisula subtruncata***	4.2
	Gastrossacus spinifer	46.9	*Pharus legumen*	4.1
	Mediomastus fragilis	44.1	*Glycera tridactyla*	3.4
	Hesionura elongata	24.6	*Spiophanes bombix*	2.8
	Glycera lapidum	14.9	*Orchomenella nana*	2.3
	Copepodes	14.5	*Ampelisca brevicornis*	2.2
	Spisula subtruncata	13.8	*Spio decoratus*	2.0
	Paradoneis lyra	10.6	Ampelisca sp.	1.7
	Thracia papyracea	9.3	*Nephtys assimilis*	1.7
			Phaxas pellucidus	1.6
			Bathyporeia guilliamsoniana	1.6
			Magelona filiformis	1.6

Table 16. Near shore shelf off Aveiro. Benthic macrofauna succession from the offshore gravely sand community to the inshore fine/very fine sand community. The table was constructed using species contributing at least 3% of the total site abundance. Shaded values indicate the higher abundance value for each species.

	Gravely sand	Fine/very fine sand
Nematodes	232.2	
Polygordius appendiculatus	205.4	
Pisione remota	94.3	
Aonides oxycephala	73.4	
Protodorvillea kefersteini	57.9	
Hesionura elongata	24.6	
Gastrossacus spinifer	46.9	0.5
Copepods	14.5	1.0
Spisula subtruncata	13.8	4.2
Spio decoratus	3.5	2.0
Mediomastus fragilis	44.1	51.0
Euspira nitida	0.6	0.8
Anomura	0.2	0.4
Magelona johnstoni	0.3	32.2
Urothoe pulchella	0.1	0.6
Nassarius reticulatus	0.1	0.9
Phaxas pellucidus	0.1	1.6
Bathyporeia guilliamsoniana	0.1	1.6
Nephtys assimilis	0.1	1.7
Orchomenella nana	0.1	2.3
Magelona filiformis		1.6
Ampelisca sp.		1.7
Ampelisca brevicornis		2.2
Spiophanes bombix		2.8
Glycera tridactyla		3.4
Pharus legumen		4.1
Owenia fusiformis		5.7
Donax cf.semistriatus		6.4

The ordination of the biological data suggests two very contrasting benthic assemblages for the shelf area under study, as no continuity exists between the sites located on the positive (K, L, M and N) and the negative pole of axis 1 (A to J) (cf. Figure 30). These two benthic assemblages, in fact, only have a few shared species, namely dominant ones, and their primary biological variables, such as species richness and abundance, present very different values (cf. Tables 15 and 16).

The relationship between the three acoustic classes and the sediment types is presented in Figure 31, where it is possible to observe that: class A includes all the coarser sands (medium, coarse and pebbly sand and sandy gravel), class B includes very fine sand and class C fine sand.

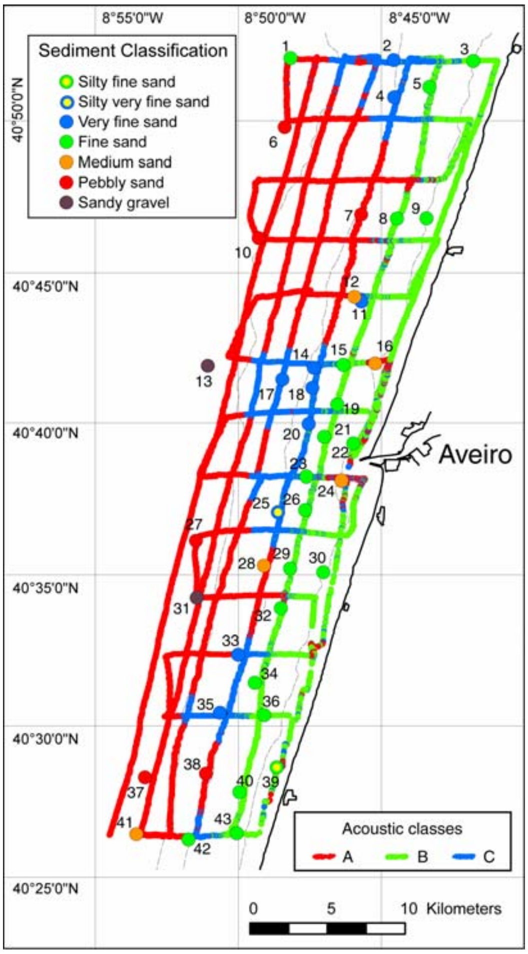


Figure 31. Near shore shelf off Aveiro. Spatial distribution of the acoustic classes A, B and C, obtained at the optimal split level. Each sampling site is represented on top of the acoustic survey lines, showing the respective sediment classification.

The relationship between these two data sets was consistent, irrespective of water depth, with the few shallower areas where the acoustic class A was identified (at the entrance of Ria de Aveiro) also being classified as medium sand (sites 16 and 24, cf. Figure 31 and Table 14). There was a single exception, with site 1, classified as fine sand, being consigned to class A (cf. Figure 31 and Table 14). Apart from such consistency, there were however several sediment grain-sizes not differentiated by the acoustic data splits, namely the coarser sands within acoustic class A.

Concerning the relationship between the acoustic classes and the biological data (Figure 32), it is possible to observe that: the sampling sites located within class A (K, L, M and N), are all plot close to each other on the positive pole of the correspondence analysis axis 1 (cf. Figure 30), while the remaining sampling sites (A to J), all fell on the negative side of the same axis (cf. Figure 30). They belong to classes B and C, and so a mismatch between the optimal acoustic classes splits (3 classes) and the biological community data is noticed (2 assemblages).

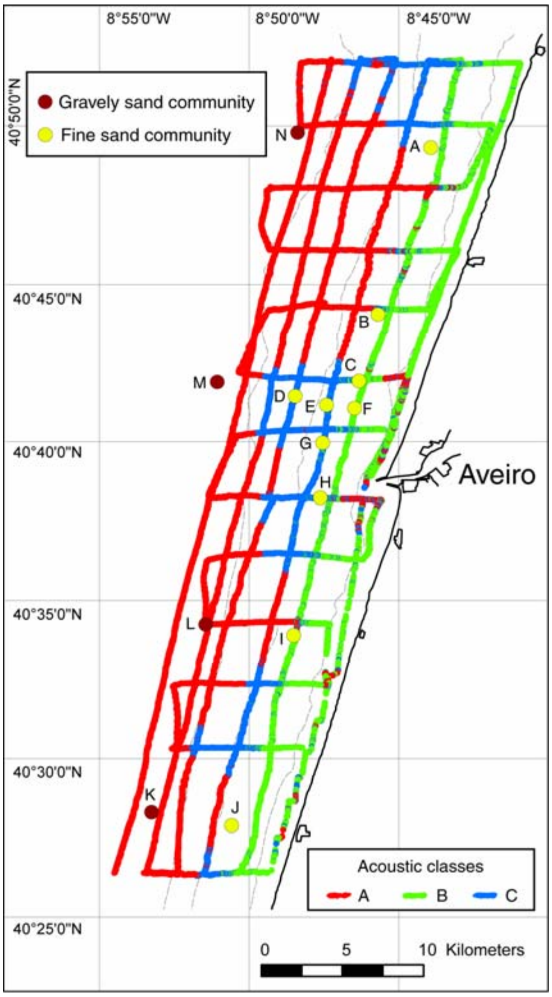


Figure 32. Near shore shelf off Aveiro. Spatial distribution of the acoustic classes A, B and C, obtained at the optimal split level. Each sampling site for the study of the benthic communities is represented on top of the acoustic survey lines, showing the respective biological group obtained by correspondence analysis (brown: gravely sand community; yellow: fine/very fine sand community).

Although the benthic data does not support the acoustic split into three acoustic classes (cf. Figure 30 and 32), it was noticed from the acoustic classification that from the first to the second acoustic split, the acoustic class A remains almost unchanged, whereas classes B and C were mainly produced from the subdivision of the previous class B, obtained at the first split (Figure 33). Splitting the acoustic data into two classes coincides with the major benthic assemblages in the shelf area under study, and render it ecologically the most meaningful and interpretable.

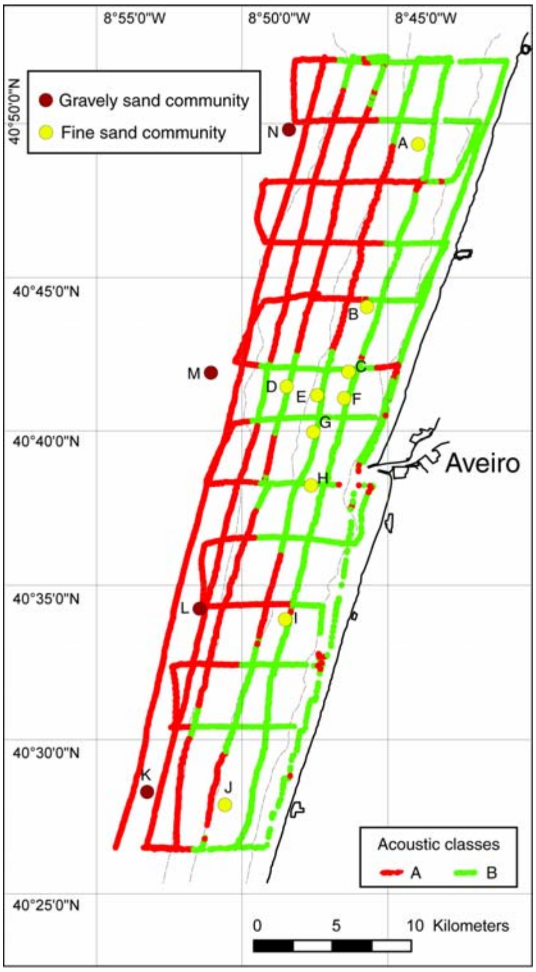


Figure 33. Near shore shelf off Aveiro. Spatial distribution of the acoustic classes A and B, obtained at the first split level. Each sampling site for the study of the benthic communities is represented on top of the acoustic survey lines, showing the respective biological group obtained by correspondence analysis (brown: gravely sand community; yellow: fine/very fine sand community).

3.4 Continental shelf off Aveiro

3.4.1 Acoustic pattern

The results of the acoustic classification for the continental shelf off Aveiro are given in Table 17.

Table 17. Continental shelf off Aveiro. Acoustic classification statistics obtained by manual clustering up to the fourth split (five classes). Total Score = sum of the scores of the individual classes; CPI = cluster performance index; CPI rate = [CPI (n) – CPI (n-1)] / CPI (n-1), where n is the split number.

Split	Number of classes	Total Score	CPI	CPI rate
0	1	13771545.75	_	_
1	2	4307544.72	2.88	_
2	3	774451.82	17.97	5.24
3	4	610929.66	44.63	1.48
4	5	389390.51	115.97	1.59

Following the information given by the statistical descriptors Total Score and CPI rate, the best classification comprehends three acoustic classes. As the classes were subdivided, the Total Score decreased and beyond the second split (three acoustic classes), further splits had almost no impact on the Total Score (Figure 34). At this split level the CPI rate also reached the maximum value, and as such, the final acoustic classification into 3 classes was accepted.

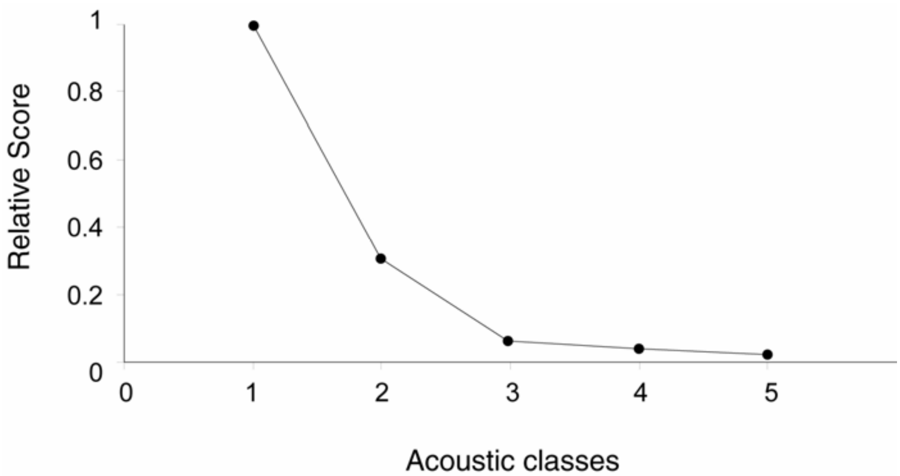


Figure 34. Continental shelf off Aveiro. Relative score, expressed as standardized values for the Total Score obtained with one acoustic class.

The geographical distribution of the three acoustic classes is presented in Figure 35.

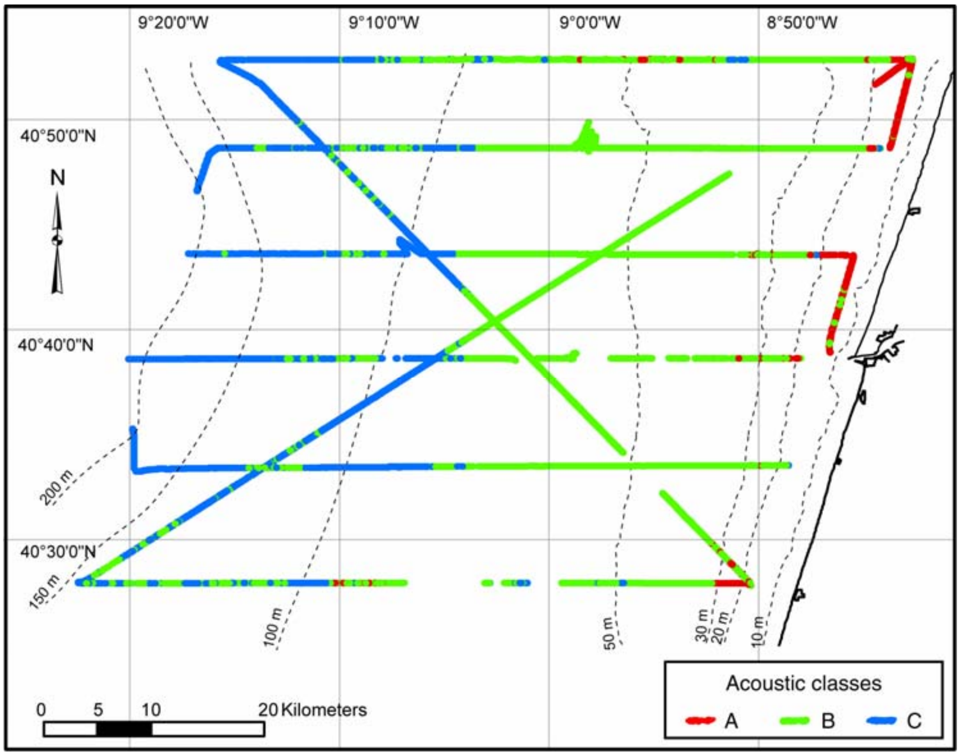


Figure 35. Continental shelf off Aveiro. GIS representation of the acoustic pattern.

The acoustic classes identified exhibit a clear spatial pattern from the near shore towards the continental shelf end, with class A closest to shore and class C the farthest.

The quality of the acoustic classification is supported by the agreement of the acoustic classes where the survey lines intersect (cf. Figure 35).

In this study no ground-truth sediment samples were collected. The interpretation of the acoustic gradient was based in sedimentary and biological data from previous works (Abrantes et al., 1997; Moreira et al., 2001 and Freitas et al. 2003a). In fact, the positioning of the longitudinal survey lines was made coincident with transects from a benthic survey held before in this coastal area (Moreira et al., 2001).

Concerning the sedimentary data, it was verified that the spatial distribution of the three acoustic classes agreed with the three main sediment assemblages described for the same area by Abrantes et al. (1997) and Freitas et al. (2003a). Class A (cf. Figure 35), located near the coast (< 30 m depth), corresponds to an area of clean fine sand identified by Freitas et al. (2003a). Class B (cf. Figure 35) in the mid shelf (30 to 90-100 m) is characterised by clean coarse sediment (very coarse and gravely sand) (Abrantes et al., 1997; Freitas et al., 2003a), while class C (cf. Figure 35) located on the outer shelf (100 to 200 m) corresponds to an heterogeneous area composed by a variety of sediments, from coarse to fine silty sand (Abrantes et al., 1997).

Although Abrantes et al. (1997) have described a complex sedimentary structure for the outer shelf and upper slope, which is poorly described by a single acoustic class (class C) it was notice that the spatial distribution of the three acoustic classes identified in the continental shelf off Aveiro is almost identical to the spatial distribution of the three benthic macrofauna communities described for the same area by Moreira et al. (2001). The distribution of these benthic communities is shown superimposed to the acoustic gradient in Figure 36.

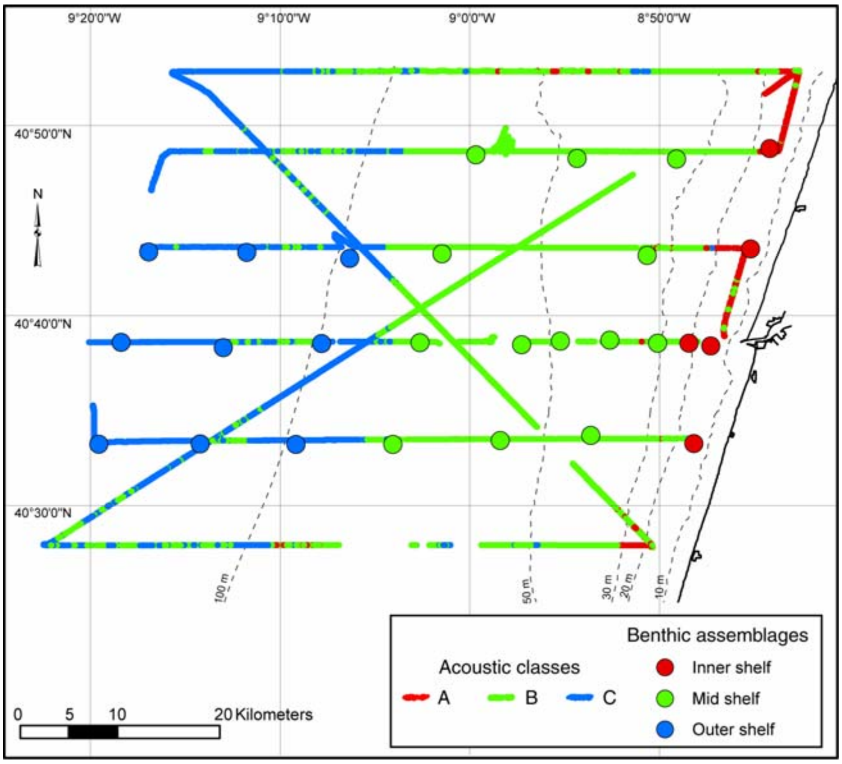


Figure 36. Continental shelf off Aveiro. Spatial distribution of the acoustic classes A, B and C, obtained at the optimal split level, jointly displayed with the macrofauna benthic communities according to Moreira et al., 2001.

3.5 Mid shelf off Lisbon

3.5.1 Acoustic pattern

In the mid shelf study area off Lisbon two acoustic surveys were performed: an initial survey using the QTC VIEW Series IV over a larger area (Figure 38) and a detailed survey covering part of the previous area, occupied by a submarine outfall, using the QTC VIEW Series V (cf. Figure 38). The survey depth ranged from 30 to 90 meters.

The results that accompany the acoustic classification for both QTC VIEW systems (Series IV and Series V) are shown in Tables 18 and 19, respectively.

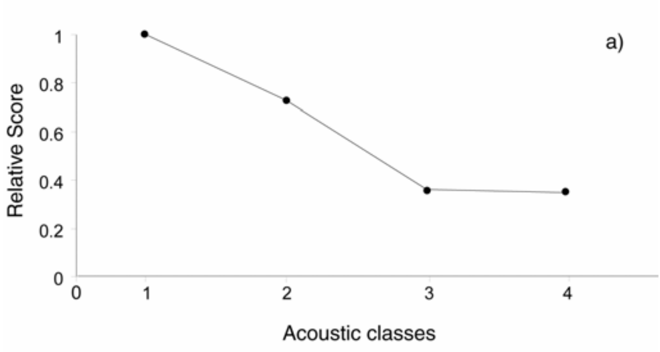
Table 18. Mid shelf off Lisbon. QTC VIEW Series IV survey. Acoustic classification statistics obtained by manual clustering up to the third split (four classes). Total Score = sum of the scores of the individual classes; CPI = cluster performance index; CPI rate = [CPI (n) – CPI (n-1)] / CPI (n-1), where n is the split number.

Split	Number of classes	Total Score	CPI	CPI rate
0	1	246178.28	_	_
1	2	178679.63	1.43	_
2	3	88535.14	5.42	2.79
3	4	85539.83	13.61	1.51

Table 19. Mid shelf off Lisbon. QTC VIEW Series V survey. Acoustic classification statistics obtained by manual clustering up to the third split (four classes). Total Score = sum of the scores of the individual classes; CPI = cluster performance index; CPI rate = [CPI (n) – CPI (n-1)] / CPI (n-1), where n is the split number.

Split	Number of classes	Total Score	CPI	CPI rate
0	1	17216.63	_	_
1	2	11105.64	1.04	_
2	3	5119.34	4.06	2.90
3	4	6625.07	10.29	1.53

For both systems, the optimal classification solution corresponds to three acoustic classes, obtained at the second split, when Total Score tended to stabilise (QTC VIEW Series IV) or reached the minimum value (QTC VIEW Series V) and the CPI rate presented the maximum value (Figure 37 and cf. Tables 18 and 19).



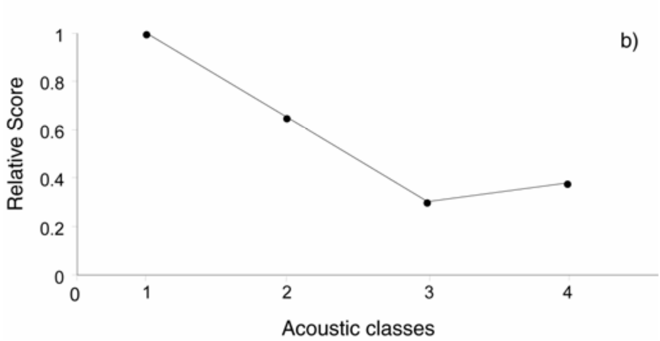


Figure 37. Mid shelf off Lisbon. Relative score, expressed as standardized values for the Total Score obtained with one acoustic class. a) QTC VIEW Series IV survey; b) QTC VIEW Series V survey.

The acoustic pattern identified in both surveys is coherent (Figure 38). The pattern issued from the survey with QTC VIEW Series V details the spatial extent of each acoustic class in the area where the submarine outfall is installed and allows to precise the extension of narrow acoustic class C, between the acoustic classes A and B, within much wider distribution.

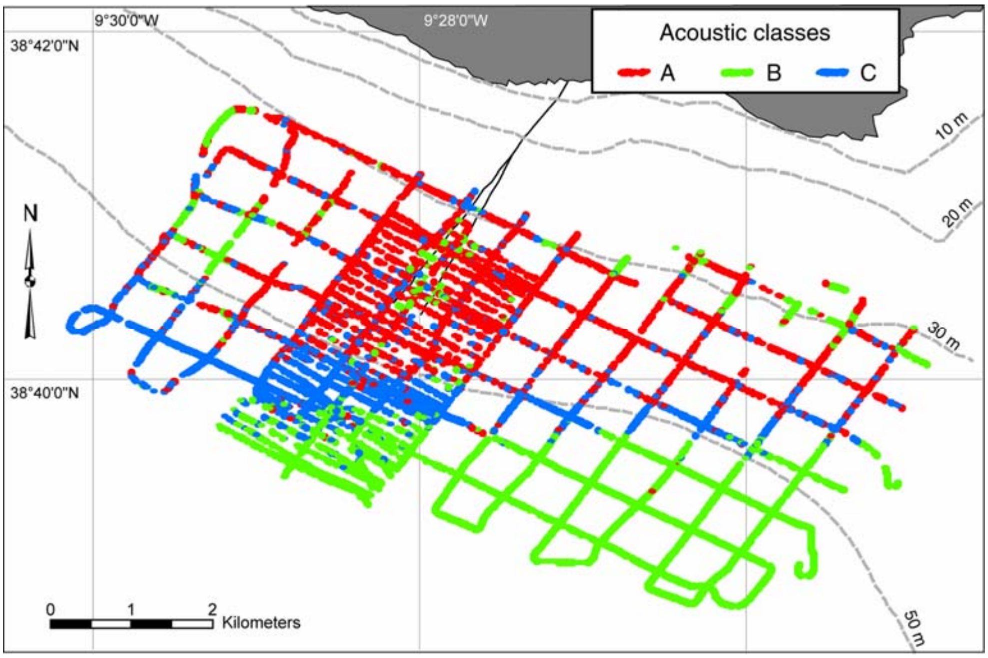


Figure 38. Mid shelf off Lisbon. GIS representation of the acoustic pattern.

3.5.2 Ground-truth

The sedimentary data issued from the analysis of the 20 ground-truth samples is presented in Table 20. The classification and ordination analysis of the sedimentary data is displayed in Figure 39. A summarised characterization of each affinity group identified is given in Table 21.

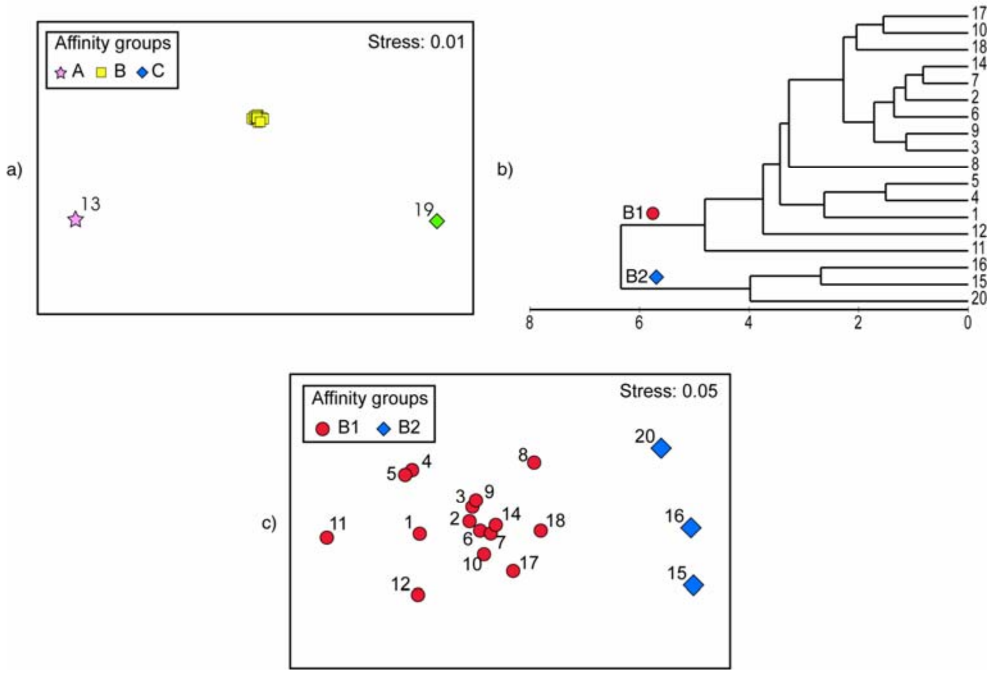


Figure 39. Mid shelf off Lisbon. Sedimentary affinity groups (A, B1, B2 and C) identified among the sampling sites. a- non-metric multidimensional scaling (NMDS) with all sampling sites; b- classification analysis, excluding sites 13 and 19; c- NMDS excluding sites 13 and 19.

Table 20. Superficial sediment grain-size analysis from the mid shelf off Lisbon. Grain-size classes (in mm) values are expressed as percent of total sediment dry weight, median value in phi units (Φ) and sediment classification according to Table 7. TVS= Total volatile Solids; RP= Redox Potential.

Site	> 2.0 (%)	1.0 – 2.0 (%)	0.5 – 1.0 (%)	0.250 – 0.500 (%)	0.125 – 0.250 (%)	0.063 – 0.125 (%)	< 0.063 (%)	Median (Φ)	TVS (%)	RP (mV)	Sediment classification
1	0.23	1.27	3.61	5.63	65.61	22.34	1.35	2.60	0.99	204.5	Fine sand
2	0.13	0.79	1.98	4.09	67.36	24.54	1.10	2.64	1.08	45.5	Fine sand
3	0.51	0.76	2.38	5.28	61.78	26.95	2.37	2.66	0.96	60.5	Fine sand
4	0.34	1.38	3.97	6.78	62.86	22.61	2.08	2.60	0.76	-67.5	Fine sand
5	0.09	1.09	3.76	6.40	71.60	15.87	1.16	2.54	0.89	-95.5	Fine sand
6	0.05	0.49	1.75	4.77	61.15	29.15	2.69	2.70	0.91	86.5	Fine sand
7	0.11	0.61	1.34	2.52	68.78	23.87	2.85	2.66	1.3	89.5	Fine sand
8	1.30	0.47	1.26	3.60	60.17	29.27	4.07	2.72	1.11	132.5	Fine sand
9	0.60	0.39	2.11	4.96	67.39	23.10	1.49	2.62	0.82	80.5	Fine sand
10	0.13	0.38	2.00	3.99	68.85	22.77	1.95	2.63	1.23	226.5	Fine sand
11	0.40	2.18	4.64	7.55	70.28	13.74	1.31	2.50	0.84	300.5	Fine sand
12	0.08	0.50	2.41	11.27	64.45	19.52	1.87	2.55	0.96	283.5	Fine sand
13	0.13	3.77	25.86	37.00	23.01	9.30	0.94	1.55	0.73	390.5	Medium sand
14	0.29	0.62	1.11	2.85	66.03	26.20	3.00	2.68	1.04	116.5	Fine sand
15	0.46	0.85	0.63	0.81	29.52	47.18	20.54	3.38	1.65	192.5	Very fine sand

Site	> 2.0 (%)	1.0 – 2.0 (%)	0.5 – 1.0 (%)	0.250 – 0.500 (%)	0.125 – 0.250 (%)	0.063 – 0.125 (%)	< 0.063 (%)	Median (Φ)	TVS (%)	RP (mV)	Sediment classification
16	0.28	0.26	0.36	0.68	35.96	43.86	18.81	3.28	2.36	-22.5	Very fine sand
17	0.03	0.24	0.97	2.70	63.39	30.36	2.41	2.73	1.04	282.5	Fine sand
18	0.40	0.25	0.52	1.45	65.47	26.14	5.86	2.72	1.77	199.5	Fine sand
19	0.03	0.08	0.18	0.27	2.90	15.33	81.26	> 4	5.48	-7.5	Mud
20	1.16	0.47	0.58	0.80	47.24	31.04	18.72	2.99	2.99	67.5	Fine sand

Table 21. Mid shelf off Lisbon. Mean values for the sedimentary data in each of the affinity group identified by classification and ordination analysis.

		Groups			
		A	B1	B2	C
Sampling sites		13	1-12,14,17,18	15,16,20	19
Total volatile solids (%)		0.73	1.05	2.33	5.48
Redox potential (mV)		390.50	129.70	79.20	-7.50
Gravel	> 2.000mm	0.13	0.31	0.63	0.03
Sand	1.000- 2.000mm	3.77	0.76	0.53	0.08
	0.500-1.000mm	25.86	2.25	0.53	0.18
	0.250-0.500mm	37.00	4.92	0.77	0.27
	0.125-0.250mm	23.01	65.68	37.57	2.90
	0.063-0.125mm	9.30	23.76	40.70	15.33
Fines	< 0.063mm	0.94	2.37	19.36	81.26
Median (Φ)		1.55	2.68	3.20	> 4.00
Sediment classification		Clean medium sand	Clean fine sand	Silty very fine sand	Mud

When including all the sampling sites in the analysis, three groups were separated in the ordination diagram (Figure 39a): group A (site 13), group C (site 19) and group B (the remaining sites). Sites 13 and 19 over-dominate the ordination pattern due to their particular grain size. The coarser sediment was observed in site 13, the single one classified as medium sand, and site 19 presents the silt and clay fraction well above the remainder (cf. Table 21). Excluding these two sites from the analysis, group B is further subdivided in subgroups B1 and B2, as shown in the classification and ordination diagrams presented in Figures 39b and 39c.

The spatial distribution of the major sedimentary affinity groups (A, B1, B2, C) is represented in Figure 40. Along the axis A (site 13) → B1 → B2 → C (site 19), the superficial sediments show a gradual increase in the median value, the silt and clay content and total volatile solids, and a decrease in redox potential (cf. Table 20). The majority of the superficial sediments in the study area correspond to fine sand with low silt and clay content (subgroup B1). With increasing depth (inshore-offshore axis) and with increasing proximity to the estuary (shelf-estuary axis), the superficial sediment becomes silty very fine sand (subgroup B2) and finally mud (group C) (cf. Table 20).

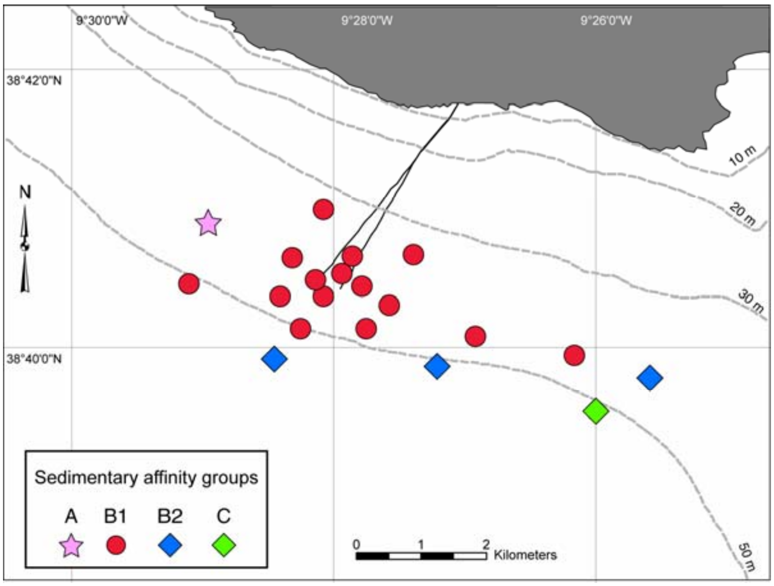


Figure 40. Mid shelf off Lisbon. GIS representation of the sedimentary affinity groups identified by multivariate analysis.

The ordination and classification diagrams of the biological data from the same ground-truth sites are shown in Figure 41.

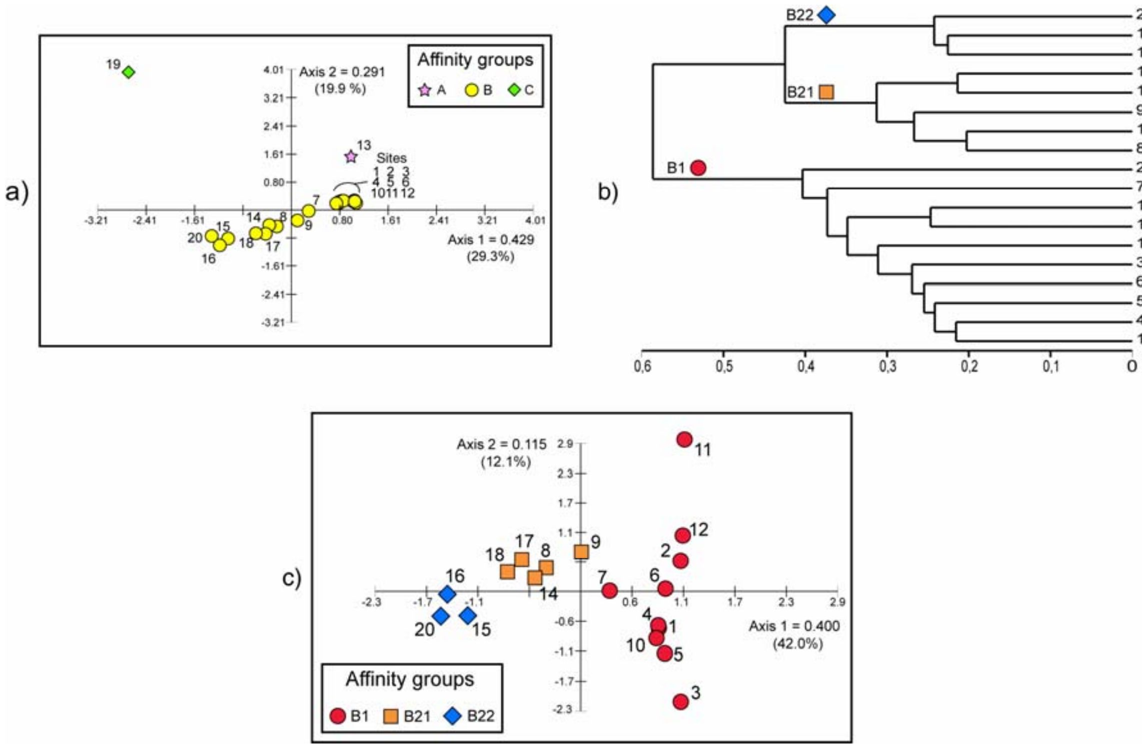


Figure 41. Mid shelf off Lisbon. Biological affinity groups (A, B1, B21, B22 and C) identified among sampling sites. a- correspondence analysis (CA) with all sampling sites; b- classification analysis, excluding sites 13 and 19; c- CA, excluding sites 13 and 19.

Sites 13 (Group A) and 19 (Group C) tend to over-dominate the ordination pattern (Figure 41a), as seen before with the sedimentary data. When excluded, the analyses show the subdivision of Group B into B1 and B2, and a further split into B21 and B22 (Figure 41b and Figure 41c). Their distribution in plane 1-2 of the correspondence analysis indicates a continuous change, rather than a sharp discontinuity between the groups (cf. Figure 41c). This is confirmed in Table 22, summarising the species succession along the biological gradient and the mean species richness and abundance in each affinity group.

Table 22. Mid shelf off Lisbon. Biological succession in the affinity groups obtained by classification and ordination analysis. Taxa include only the species whose abundance per site is higher than 3% of the site total. The highlighted values indicate the species highest mean abundance.

	Groups				
	A	B1	B21	B22	C
Sampling sites identification	13	1-7,10-12	8,9,14,17,18	15,16,20	19
Mean abundance (A/0.1m^2)	96.7	102.1	143.1	243.4	109.3
Mean species richness (S/0.3m^2)	38.0	41.3	46.0	52.0	31.0
Mean species richness (S/0.1m^2)	16.3	25.0	26.9	33.5	19.0
Pisione remota	72.0				
Glycera oxycephala	9.0				2.0
Mediomastus capensis	50.0	4.7	0.8	1.0	
Atylus falcatus	3.0	2.6			
Spionidae n. det.	10.0	0.4	2.4	1.7	
Tellina fabula	18.0	41.3	5.0		
Chaetozone setosa	52.0	61.0	2.2		
Urothoe pulchella	1.0	6.2	0.8	0.7	
Capitella spp.		27.3			
Aora typica		0.8			
Mactra corallina		9.3	1.8		
Sigalion mathildae		2.8	1.2		
Mysella bidentata		7.8	7.4	4.3	
Atylus swammerdami		4.0	3.4	0.3	
Anomura n. det.		4.7	3.0	2.0	
Glycera tridactyla	1.0	5.4	4.8	3.0	3.0
Spio decoratus	1.0	4.2	1.6	1.7	
Ampelisca brevicornis		5.0	3.0	3.0	2.0
Nassarius reticulatus	3.0	15.0	2.0	4.7	
Photis longicaudata		8.2	1.8	3.0	
Sabellaria alveolata		7.2		0.3	
Magellona filiformis	8.0	4.7	67.6	0.3	
Paraonidae n. det.	3.0	6.8	10.2	4.0	10.0
Aoridae n. det.	3.0	0.3	7.8	3.0	
Spiophanes bombix	1.0	6.8	23.0	10.0	
Hyalinoecia bilineata	8.0	11.3	89.6	125.7	
Nucula spA		0.8	2.4	12.0	1.0
Tellina pulchella		0.3	1.6	28.3	1.0
Maldanidae spA		0.2	10.8	150.7	
Spiophanes kroeyeri		0.4	9.4	31.7	6.0
Prionospio spp.	5.0	11.4	31.0	32.0	4.0
Maldanidae spB			0.2	18.0	
Lumbrinereis cf. latrelli		1.9	69.8	98.3	80.0
Chaetopteridae n. det		0.1	0.2	17.7	1.0
Abra alba		2.7	1.2	19.0	2.0
Thyasira flexuosa			3.8	23.0	16.0
Ampelisca spp.	1.0	1.6	13.2	40.3	24.0
Terebellidae n. det.		0.9	0.2	1.0	46.0
Hydrobia ulvae					17.0
Thyasira spA					19.0

The spatial distribution of the benthic affinity groups (Figure 42) identifies the same dominant patterns along the inshore-offshore and shelf-estuary directions, as observed in the spread of the sedimentary gradient (cf. Figure 40).

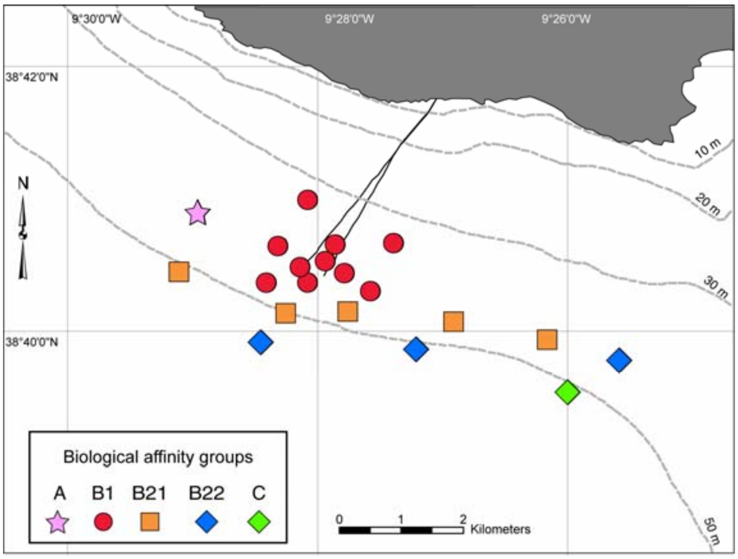


Figure 42. Mid shelf off Lisbon. GIS representation of the biological affinity groups identified by multivariate analysis.

This pattern has been consistently reported in this coastal region (Quintino et al., 2001). The succession represented by groups A (site 13) → B1 → B21 → B22 → C (site 19), is very similar to the one obtained with the sedimentary data (cf. Figure 40). At the Northwest extremity, site 13 (group A) is characterised by interstitial polychaetes (cf. Table 22). At the Southeast extremity, site 19 (group C) is characterised by faunal impoverishment (cf. Table 22), namely due to the superficial sediments high content in fines and chronic hydrocarbon contamination (Quintino et al., 2001). Between these two groups, the faunal succession corresponds to a gradual replacement of the dominant species (cf. Table 22). Except site 19, the overall tendency along this succession is for a slight increase in both species richness and abundance. Within the succession, the subgroup B21, spatially located between B1 and B22 (cf. Figure 42), is the less well characterised, with a smaller number of dominant species. This agrees with its position in the ordination, closer to the origin and between B1 and B22 (cf. Figure 41c).

The joint geographical distribution of the acoustic classes, the sedimentary and biological affinity groups is shown in Figure 43.

a)

b)

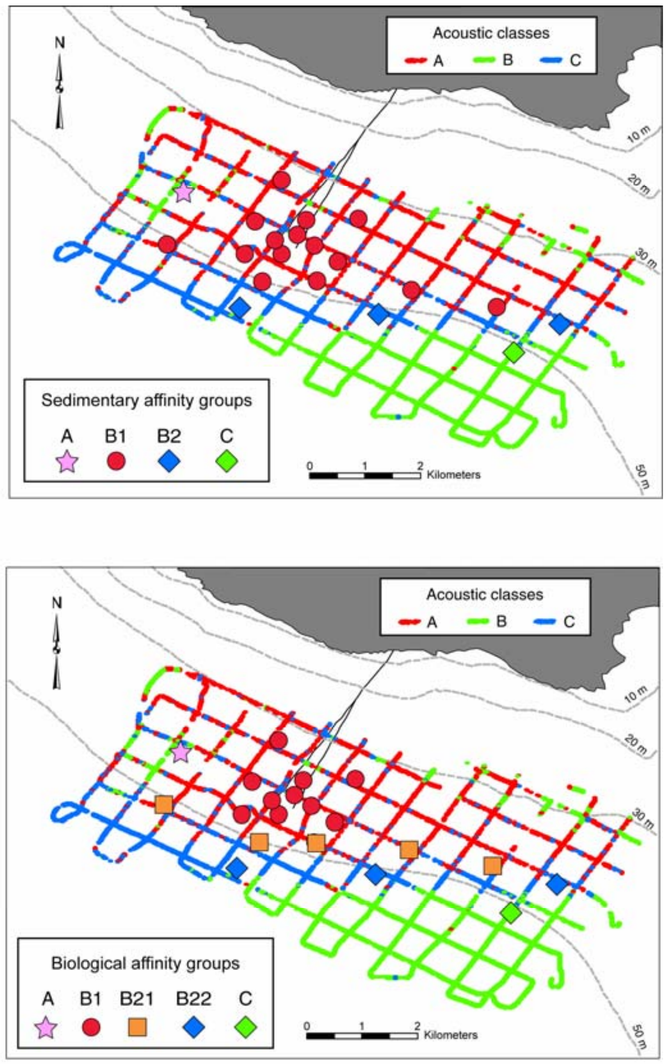


Figure 43. Mid shelf off Lisbon. Spatial distribution of the acoustic classes A, B and C, obtained at the optimal split level, jointly displayed with the sedimentary (a) and the biological affinity groups (b).

The acoustic classes present a close relationship with the sedimentary and the biological groups (cf. Figure 43). The acoustic class A, to the Northwest, is predominant in the survey area and corresponds to the region occupied by fine sand with low silt and clay content (sedimentary group B1, Figure 43a and Table 21; biological group B1, Figure 43b and Table 22). Class B, located between classes A and C, corresponds well with the area occupied by silty very fine sand (sedimentary group B2, Figure 43a and Table 21; biological group B22, Figure 43b and Table 22). Finally, class C, to the Southeast, corresponds to the area occupied by mud with silt and clay content above 75% (sedimentary group C, Figure 43a and Table 21; biological group C, Figure 43b and Table 22). A single ground-truth sample was taken inside the acoustic class C (site 19).

Although a close relationship was notice between the acoustic and the sedimentary and biological data, some of the acoustic areas were interpreted using one or very few ground-truth samples. This lead to a specific validation survey, conducted *a posteriori*, in which the number of ground-truth sampling sites was increased to 60 and their positioning based on the acoustic diversity previously identified.

The sedimentary data obtained in this validation survey is presented in Table 23. Figure 44 presents a principal component analysis diagram, displaying in axis 1-2 the affinity groups identified in this dataset by average clustering (A1, A2a, A2b and B). A summarised characterisation of these groups is shown in Table 24.

The coarser sediment with the highest redox potential values corresponds to group A1. Group A2a corresponds to fine sand with the silt and clay fraction below 5%. Very fine sand with the silt and clay fraction above 5% characterises group A2b. Finally, group B includes the sampling sites with the highest values for fines content, total volatile solids and median grain-size, and the lowest values for the redox potential (cf. Table 24). Figure 45 presents photographs, from the superficial sediment layer, taken at each of these groups.

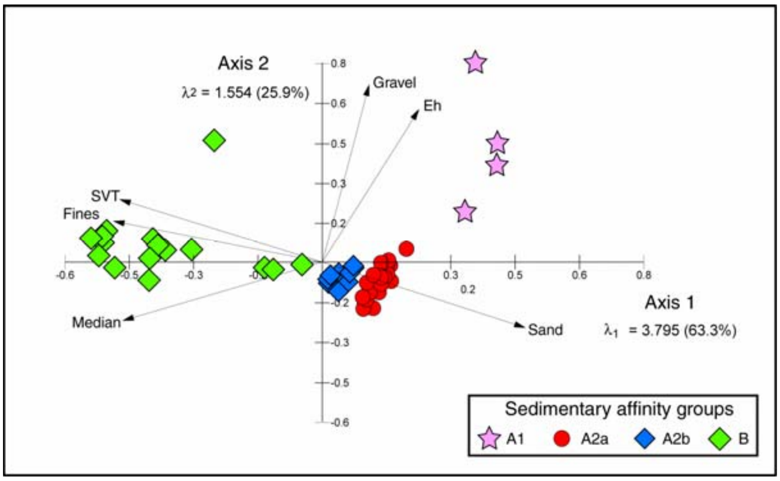


Figure 44. Mid shelf off Lisbon. Sedimentary affinity groups A1, A2a, A2b and B, identified by cluster analysis, plotted on axes 1 and 2 of a principal components analysis. Data from the validation survey conducted *a posteriori*.

Table 23. Mid shelf off Lisbon. Superficial sediment grain-size analysis from the validation survey conducted *a posteriori*. Grain-size classes (in mm) values are expressed as percent of total sediment dry weight, median value in phi units (Φ) and sediment classification according to Table 7. TVS= Total volatile Solids; RP= Redox Potential.

Site	> 2.0 (%)	1.0 – 2.0 (%)	0.5 – 1.0 (%)	0.250 – 0.500 (%)	0.125 – 0.250 (%)	0.063 – 0.125 (%)	< 0.063 (%)	Median (Φ)	TVS (%)	RP (mV)	Sediment classification
1	0.37	1.58	3.39	4.55	56.82	30.30	2.98	2.71	1.37	69	Fine sand
2	0.24	1.57	4.22	7.51	69.33	15.85	1.27	2.53	0.82	-78	Fine sand
3	0.14	1.37	3.53	6.05	53.95	32.36	2.61	2.72	1.00	-77	Fine sand
4	0.38	1.17	2.91	4.44	59.49	29.05	2.56	2.69	1.08	-69	Fine sand
5	0.15	1.08	3.18	5.31	66.23	21.95	2.11	2.61	0.90	2	Fine sand
6	0.48	1.28	4.72	8.80	57.09	25.46	2.17	2.61	0.89	41	Fine sand
7	0.08	0.56	1.63	2.73	49.97	40.30	4.72	2.90	1.12	52	Fine sand
8	0.04	0.35	0.92	2.82	55.82	34.00	6.06	2.82	1.04	59	Fine sand
9	0.09	0.53	1.89	3.94	57.32	32.97	3.25	2.76	1.21	-4	Fine sand
10	0.17	0.75	2.41	3.88	57.57	32.66	2.56	2.74	1.15	-34	Fine sand
11	0.33	1.42	2.95	5.80	65.45	21.42	2.62	2.60	0.90	51	Fine sand
12	0.03	0.60	3.25	14.07	58.61	21.62	1.83	2.55	0.70	62	Fine sand
13	0.46	6.83	37.77	43.57	9.32	1.72	0.33	1.11	1.03	326	Medium sand
14	0.08	0.50	0.98	2.22	56.72	35.23	4.26	2.81	0.90	7	Fine sand
15	0.08	0.31	0.45	1.06	44.24	43.85	10.02	3.09	1.65	51	Very fine sand
16	0.02	0.14	0.26	0.68	38.99	50.02	9.89	3.20	1.74	5	Very fine sand
17	0.17	0.29	1.25	3.37	55.56	35.92	3.44	2.81	1.29	-25	Fine sand
18	0.32	0.31	0.51	1.04	43.69	43.79	10.35	3.09	1.93	76	Very fine sand
19	0.06	0.15	0.25	0.39	4.63	16.07	78.45	> 4	6.59	-78	Mud
20	0.32	0.31	0.45	0.91	38.76	43.21	16.05	3.21	2.07	47	Very fine sand

Site	> 2.0 (%)	1.0 – 2.0 (%)	0.5 – 1.0 (%)	0.250 – 0.500 (%)	0.125 – 0.250 (%)	0.063 – 0.125 (%)	< 0.063 (%)	Median (Φ)	TVS (%)	RP (mV)	Sediment classification
21	0.07	0.90	3.70	9.11	62.09	22.22	1.90	2.58	0.99	214	Fine sand
22	0.14	0.89	2.85	8.06	59.57	25.57	2.92	2.64	0.94	90	Fine sand
23	0.00	19.37	65.44	5.90	2.20	1.06	0.43	0.38	0.99	393	Coarse sand
24	0.00	17.59	63.39	8.97	0.80	0.28	0.17	0.37	1.13	398	Coarse sand
25	0.14	0.23	0.39	0.85	30.60	53.13	14.67	3.34	2.07	45	Very fine sand
26	0.18	0.18	0.26	0.49	12.36	56.24	30.29	3.65	3.55	44	Very fine sand
27	0.36	0.01	0.03	0.09	2.44	28.41	68.67	> 4	6.55	65	Mud
28	0.07	0.02	0.05	0.18	2.70	30.42	66.57	> 4	5.75	44	Mud
29	0.19	0.16	0.19	0.35	7.75	54.63	36.74	3.76	3.16	54	Very fine sand
30	0.28	0.62	0.86	1.22	43.48	41.70	11.83	3.08	2.33	64	Very fine sand
31	0.29	1.09	1.28	2.22	55.31	35.39	4.42	2.82	1.10	57	Fine sand
32	0.05	0.58	1.74	3.20	56.80	31.48	6.15	2.78	1.23	53	Fine sand
33	0.05	0.40	1.96	7.20	58.70	28.76	2.94	2.69	1.40	153	Fine sand
34	0.00	25.18	15.92	8.86	15.91	4.72	0.85	-0.15	1.41	232	Very coarse sand
35	0.43	2.18	3.78	5.92	62.18	23.21	2.29	2.61	0.92	37	Fine sand
36	0.20	0.95	2.74	4.41	62.41	26.97	2.31	2.67	1.02	73	Fine sand
37	0.24	2.10	4.72	7.69	59.80	23.09	2.36	2.59	1.08	34	Fine sand
38	0.04	0.08	0.11	0.25	2.27	25.03	72.21	> 4	5.53	63	Mud
39	0.18	0.07	0.10	0.25	2.48	31.89	65.03	> 4	5.81	-100	Mud
40	0.16	0.14	0.29	0.87	47.52	42.30	8.72	3.02	2.08	94	Very fine sand
41	0.12	0.30	1.23	3.38	53.51	37.14	4.32	2.84	1.36	142	Fine sand
42	0.37	1.31	2.81	5.02	58.75	28.64	3.10	2.69	0.97	127	Fine sand
43	0.13	1.12	2.62	4.79	65.69	22.61	3.05	2.63	1.79	59	Fine sand
44	0.16	1.21	3.46	4.77	66.65	20.85	2.90	2.61	1.48	72	Fine sand
45	0.06	0.45	1.15	2.68	62.08	30.75	2.83	2.74	1.24	139	Fine sand
46	0.05	0.27	0.48	1.22	46.59	46.87	4.52	3.03	1.33	69	Very fine sand
47	0.01	0.05	0.08	0.37	25.19	64.28	10.02	3.38	2.52	42	Very fine sand
48	0.01	0.10	0.11	0.29	2.96	23.30	73.23	> 4	5.47	2	Mud
49	0.03	0.02	0.05	0.12	1.25	7.96	90.57	> 4	6.39	-34	Mud
50	0.03	0.02	0.05	0.29	1.20	7.21	91.20	> 4	6.70	66	Mud
51	0.00	0.02	0.05	0.20	0.63	3.33	95.78	> 4	6.86	30	Mud
52	0.02	0.02	0.04	0.13	1.14	5.04	93.61	> 4	6.14	21	Mud
53	0.35	0.15	0.10	0.21	1.88	9.74	87.56	> 4	7.35	39	Mud
54	0.12	0.22	0.34	0.69	13.48	25.14	60.01	> 4	4.97	71	Mud
55	0.64	1.59	2.12	2.97	63.08	27.12	2.47	2.68	1.12	59	Fine sand
56	0.00	10.55	6.23	2.15	15.46	9.18	43.38	3.28	8.11	210	Very fine sand
57	0.24	0.42	0.81	1.38	58.16	32.78	6.22	2.81	1.23	39	Fine sand
58	0.33	1.31	1.70	2.00	66.52	23.65	4.50	2.67	1.56	67	Fine sand
59	1.19	0.89	0.86	0.95	13.99	56.14	25.98	3.57	2.35	69	Very fine sand
60	0.24	0.66	0.76	1.79	37.23	48.21	11.12	3.19	1.57	119	Very fine sand

Table 24. Mid shelf off Lisbon. Characterisation of the sedimentary groups identified by cluster analysis in the validation survey conducted *a posteriori*. Mean value and standard deviation (sd) for each sedimentary group identified by multivariate analysis in the validation survey conducted *a posteriori*. Fines: fraction under 0.063 mm; Sands: fraction between 0.063-2.000 mm; gravel: fraction above 2.000 mm.

	Affinity groups							
	A1		**A2a**		**A2b**		**B**	
Sampling sites	13,23,24,34		1-12,14,17,21,22,31-33,35-37,41-46,55,57,58		15,16,18,20,25,30,40,47,60		19,26-29,38,39,48-54,56,59	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
Redox potential (mV)	337.3	77.47	49.7	66.07	60.3	33.04	35.4	69.92
Total volatile solids (%)	1.1	0.19	1.1	0.24	2.0	0.31	5.7	1.55
Fines (%)	0.4	0.29	3.3	1.29	11.4	2.42	67.4	22.88
Sand (%)	88.7	12.54	96.5	1.25	88.4	2.48	31.6	22.02
Gravel (%)	10.9	12.30	0.2	0.15	0.2	0.12	1.0	3.23
Median (Φ)	0.7	0.32	2.7	0.11	3.2	0.12	> 4,0	-
Sediment classification	Clean coarse sand		Clean fine sand		Silty very fine sand		Mud	

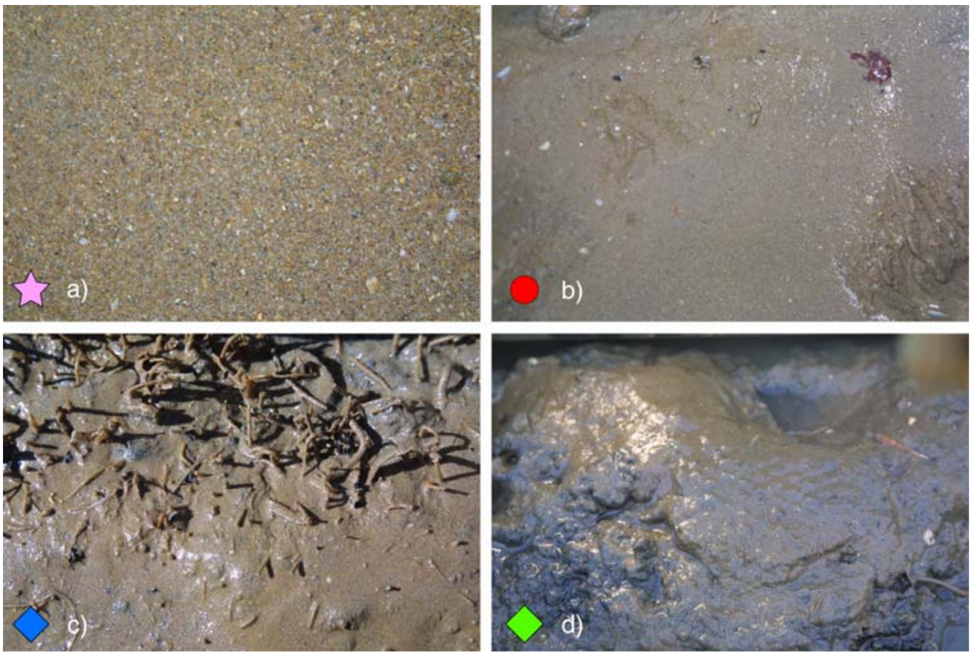


Figure 45. Photographs of the superficial sediment layer in each sediment type: a) loose coarse sands, located towards the outer shelf; b) fine sand with low silt content; c) narrow belt of silty very fine sand; d) impoverished mud with very high silt content, located towards the entrance of the estuary. The coloured symbols correspond to the sedimentary affinity groups represented in Figure 46.

The spatial distribution of the sedimentary affinity groups is presented in Figure 46.

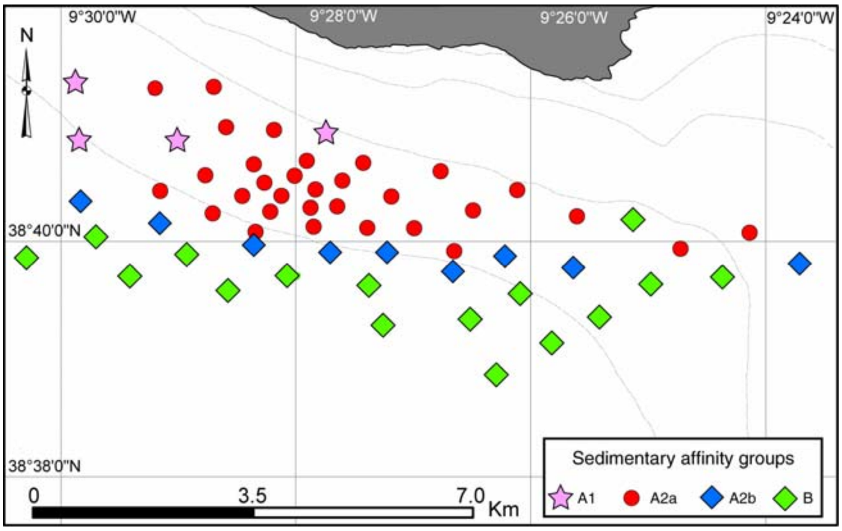


Figure 46. Mid shelf off Lisbon. GIS representation of the sedimentary affinity groups identified by multivariate analysis in the validation survey data.

The sedimentary data resulting from the 60 sampling sites analysis showed a progression through the groups A1→A2a→A2b→B, corresponding to a gradual increase of the median grain-size value, fines and total volatile solids content. The majority of the study area corresponds to fine sand with low fines content (Group A2a, cf. Figure 46 and Table 24). To the Northwest part of the survey region, there is a relatively small area characterised by loose coarse clean sand. The fines proportion of the superficial sediments increases with the increasing depth, along the inshore-offshore axis, and towards the estuary, along the shelf-estuary axis. Mud with high silt and clay content characterise the end part of this gradient (group B, cf. Figure 46 and Table 24). The transition between the two major sediment groups, clean fine sand and mud is made through a relatively narrow area of very fine silty sand (group A2b, cf. Figure 46 and Table 24).

Concerning the biological data obtained in the same 60 sites, Figure 47 displays the affinity groups identified by cluster analysis, A1, A2a, A2b and B on Axes 1 and 2 of a correspondence analysis. Table 25 shows the mean species richness and abundance for each group.

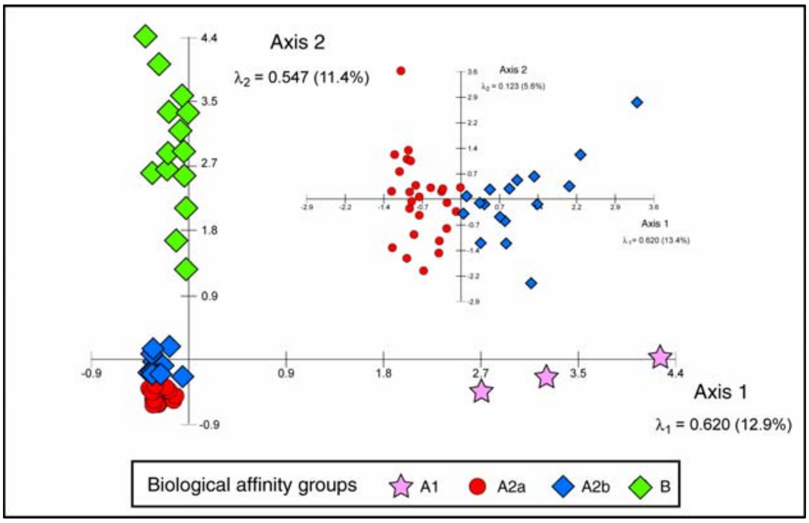


Figure 47. Mid shelf off Lisbon. Biological affinity groups A1, A2a, A2b and B, identified by cluster analysis in the validation survey data, plotted on axes 1 and 2 of a correspondence analysis. The inset diagram details the ordination of sub-groups A2a and A2b, after deletion of the groups A1 and B.

Table 25. Mid shelf of Lisbon. Mean species richness (S) and mean abundance (A) per unit sample with the corresponding standard deviation (sd) for each biological group identified by multivariate analysis in the validation survey conducted *a posteriori*.

	Affinity groups							
	A1		**A2a**		**A2b**		**B**	
Sampling sites	13,23,24		1-7,10-12,17,21,22,32-37,42-45,55,56,58		8,9,14-16,18, 20,25,30,31,40,41,46,57, 59,60		19,26-29,38,39,47-54	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
A/0,1m^2	529.3	420.02	223.0	68,75	288.6	131.33	52.5	36.95
S/0,1m^2	37.0	8.19	41.4	8.48	48.6	10.79	20.7	8.18

The distribution of the biological groups in the correspondence analysis (cf. Figure 47) indicates a continuous change between the groups, which is confirmed by the species succession presented in Table 26. Although the analysis was conducted with the whole set of 236 species, Table 26, for reasons only related to the simplicity of representation, it only includes a subset, which arguably best represents the whole group of species. This subset, comprising 26 species, was obtained using the PRIMER routine BVSTEP. With this routine, a subset of species was determined in order to produce a Bray-Curtis resemblance matrix with a Spearman correlation of 0.95 with the Bray-Curtis resemblance matrix obtained with the whole set of species. An initial subset of 12 species was found matching the correlation threshold of 0.95. After removing this initial subset, a second subset of 14 species also attained this correlation value with the original data matrix. Once these 14 species were excluded, no further species subset was obtained which could match the requested correlation threshold. Jointly, the matrix with the selected 26 species presents a Spearman correlation of 0.977 with the original data matrix.

Table 26. Mid shelf of Lisbon. Biological succession in the affinity groups identified in the validation survey conducted *a posteriori*. The taxa are represented by their mean abundance per unit sample ($0.1m^2$) in each group and include the species subset that best represents the whole data matrix. Highlighted values indicate the group where each species presents the highest mean abundance.

	Groups			
	A1	**A2a**	**A2b**	**B**
Polygordius appendiculatus	**103.67**			
Nematoda n.i.	**48.67**	0.04	0.56	
Paradoneis cf. lyra	**25.33**		0.06	2.27
Spio decoratus	**14.67**	8.08	4.94	0.07
Spiophanes bombyx	**11.00**	7.73	10.06	0.07
Tellina fabula		**24.23**	1.69	
Siphonoecetes kroyeranus	0.33	**5.19**	0.50	
Euspira nitida	1.33	**2.81**	1.63	
Chaetozone setosa	4.67	**25.50**	9.69	0.33
Magelona johnstoni	0.33	**14.58**	4.88	0.40
Nemertea n.i.	7.00	**7.38**	6.31	0.80
Ampelisca brevicornis		**8.38**	3.94	0.60
Lumbrinereis latreilli	1.00	1.46	**46.81**	10.73
Hyalinoecia bilineata	2.00	9.65	**30.88**	0.40
Glycera tridactyla	1.00	6.23	**7.06**	0.67
Abra alba	0.67	3.62	**13.31**	0.27
Magelona filiformis		3.92	**7.50**	
Thyasira flexuosa		0.08	**2.94**	1.33
Tellina compressa		0.58	**8.44**	1.80
Ampelisca sp.		8.69	**9.13**	1.13
Prionospio fallax		7.88	**12.81**	0.40
Notomastus latericeus		0.04	0.06	**2.00**
Poecilochaetus serpens			0.19	**0.53**
Paraprionospio pinnata			0.31	**1.20**
Heteromastus filiformis				**1.67**
Thyasira sp.				**2.33**

The spatial pattern represented by the biological affinity groups (Figure 48) also follows the inshore-offshore and the shelf-estuary directions, as identified earlier by the sedimentary groups.

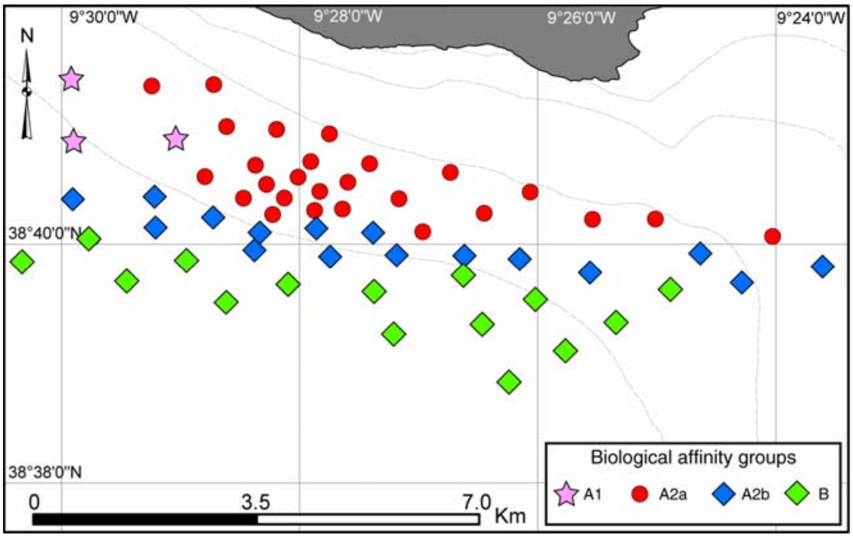


Figure 48. Mid shelf off Lisbon. GIS representation of the biological affinity groups identified by multivariate analysis in the validation survey data.

At the Northwest extremity, group A1 presents the highest species abundance and is dominated by small interstitial annelids (cf. Tables 25 and 26), in agreement with the fact that this region is constituted by loose coarse sand with low fines content (cf. Table 24). At the Southeast extremity, group B is characterised by faunal impoverishment, both in species and numbers of specimens (cf. Tables 25 and 26), also in agreement with the high fines content of this region, and the overall higher sediment contamination of these muddy areas closer to the mouth of the Tagus Estuary, when compared to the inshore sandy sediments (Quintino et al., 2001). The groups A2a and A2b present the highest values of species richness and are characterised by a gradual succession of dominant species (cf. Tables 25 and 26). The two major benthic assemblages correspond to the affinity groups A2a and B (cf. Figure 48). The transition between these is made through a relative narrow belt, presenting the highest mean species richness (group A2b, cf. Figure 48 and Table 25). This succession has a clear correspondence in the sedimentary groups (cf. Figures 46 and 48).

From the presented results it is possible to conclude that the sedimentary and the biological data both indicate four soft bottom benthic habitats for this coastal area, as gradients from inshore to offshore and shelf to estuary.

The acoustic pattern identified reveals a very close agreement with the distribution of these habitats, which, as shown in Figure 49, does not follows the overall depth gradient, thus indicating the independence of the acoustics from depth.

a)

b)

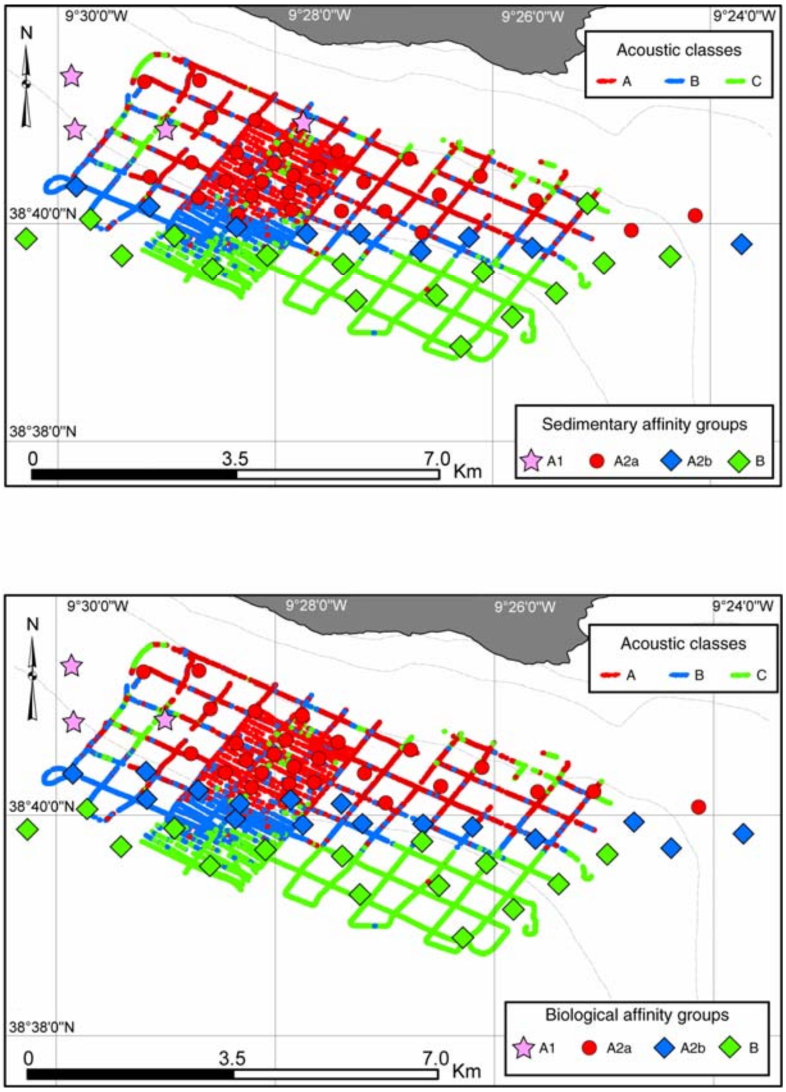


Figure 49. Mid shelf off Lisbon. Spatial distribution of the acoustic classes A, B and C, obtained at the optimal split level, jointly displayed with the sedimentary (a) and the biological affinity groups (b) identified in the validation survey data.

The increase in the number of ground-truth sampling sites from 20 to 60, clearly confirms the spatial model previously suggested by the acoustic method, which in some cases was sustained by a single or only very few sampling sites. This is the case of the large area located to the Southeast occupied by the mud habitat (acoustic class C, cf. Figure 49a), which was previously supported by a single ground-truthed sample, and the narrow transition belt of silty very fine sand, characterised by the tubicolous polychaete (acoustic class B, cf. Figure 49a), previously supported by only three ground-truthed samples. The large extent of clean fine sand (acoustic class A, cf. Figure 49a) is also confirmed by a larger number of samples, although this habitat was already well represented by ground-truthed samples by the first sampling survey.

At the Northwest extremity, the increase in sampling sites also confirms the presence of a coarser sand habitat, which in the previous study was also indicated by a single sample (cf. Figure 49a). The fact that these coarser sediments, inhabited by a particular faunal assemblage, have no corresponding acoustic class is probably because the acoustic survey covered a small spatial extent and hence only a small number of echoes were obtained in such sediment type. This could have limited the ability of the acoustic classification software to establish a separate acoustic class. However, those areas are not classified as the surrounding class A, but appear classified as class C, which corresponds to the mud habitat (cf. Figure 49a). A similar situation was observed in other inshore survey areas, where again intrusions of class C were noticed (cf. Figure 49a). In these other cases, the intrusions of class C did correspond to heterogeneous sediment identified by the ordination analysis and characterised by higher proportions of both silt/ clay and gravel fractions. When compared to the clean fine sand and the silty very fine sand, these other sediments have one common characteristic: they are much less compact, allowing the grab sampler to penetrate deeper.

CHAPTER 4 - DISCUSSION

4. Discussion

This thesis emphasises the use of a single-beam acoustic ground discrimination system (QTC VIEW Series IV and V) and seeks to highlight their advantages and limitations for the characterisation and mapping of sublittoral bottom benthic biotopes. Whenever possible, the acoustic surveys were accompanied by ground-truth grab sediment sampling for the acquisition of sedimentary and biological data. The main objective was to evaluate the reliability of the acoustic system for the remote sensing of benthic biotopes on a range of environmental situations over the coastal shelf depth range (Freitas et al., 2001). Thus, the acoustic survey areas included a coastal lagoon with very contrasting superficial sediment types, the majority of which shallower than 5 meters depth; an artificial bar channel and adjacent near shore shelf, with a depth range from 5 to 15 meters and characterised by a range of sandy sediments submitted to strong tidal currents (Freitas et al., 2005); a near shore shelf area, with survey depth ranging from 5 to 35 meters characterised by a smooth slope and contrasting macrofauna benthic communities, installed on gravely sands and fine/very fine sand, both with very low silt content (Freitas et al., 2003a); a mid shelf area, with a depth range from 30 to 90 meters, with a steeper slope and sediment types including clean sands but also muds with more than 70% silt and clay content (Freitas et al., 2003b); and finally a survey area covering the full depth range of the coastal shelf, from the near shore up to 200 meters depth.

The survey conducted in the lagoon of Óbidos revealed that, even though the QTC VIEW Series V was developed to operate in shallow water (QTC VIEW Series V, 2002), the acoustic pattern obtained did not show a close relationship with the measured bottom characteristics. Although the final acoustic result, comprehending 3 acoustic classes, showed high coherence at the intersecting points in the survey lines, the identified acoustic classes did not present a close correspondence neither to the sediment types identified nor to the biological descriptors, namely the algae or the molluscs distribution. Overall, nevertheless, a relative agreement was obtained between the two major acoustic classes and the two major lagoon bottom environments, namely the sandy biotopes from the entrance and navigation channels and the mud biotopes from the central body and inner areas.

Although the acoustic data acquired in the lagoon was carefully checked for errors and all possible misleading portions of data were eliminated before the classification analysis, it was not possible to identify one main reason for the mismatch between the acoustic classes and the sediment/benthic information. In this survey, we used one of the first versions of the QTC VIEW Series V acquisition software, which performs less well than today's versions in terms of real time quality assurance of the sampled data. The simple fact that the survey was done in very shallow water (the mean depth survey was approximately 2 m), could limit the performance of the acoustic system, namely due to the risk of the acquisition of second echoes and/or ping collision. In fact, the few known studies conducted with the Series V, all carried out in deeper areas than ours, also did not reveal successful bottom classification results (Riegl and Purkis, 2005; Hutin et al., 2005).

The acoustic classification for the lagoon survey could also reflect the complexity of the bottom characteristics of this coastal area. The high diversity of sediments, often heterogeneous, algae coverage, sometimes extending well into the water column, bivalves and other macrofauna species, could result in acoustic classes that reflect not a given predominant bottom feature but a mixture of the environmental factors that characterise each sampling point. For example, since the frequency used allows some penetration of the sound energy into the superficial sediment, in areas where the bottom is covered by algae, the acoustic data could reflect not only the type of sediment but also the information from both the sediment and the algae covering. Indeed, Anderson et al. (2002) revealed that the acoustic system QTC VIEW Series IV was able to distinct different marine habitats, namely characterised by the presence of macroalgae. This observation could be extrapolated to the bivalves present at the sediment surface/subsurface and in general to the benthic community assemblages. Even so, it was not possible to determine a group of features that characterises each acoustic class. The different sediment compactness is another important factor that increases the diversity of acoustic responses and therefore could conduct to the misclassification verified.

In addition to the bottom composition, it has been shown that a steep bottom slope could greatly affect the QTC VIEW Series V performance (Hutin et al., 2005). Nevertheless, in the Lagoon of Óbidos this attribute should be not relevant for the acoustic analysis since only a few restricted areas present such steep slopes.

Besides possible limitations of the QTC performance related to complex mixture of bottom characteristics of the surveyed area (heterogeneous bottoms, muddy bottoms with and without algae, muddy areas with gas accumulation in the most inner part of the lagoon, muddy areas over sand in some margins), the results obtained at the lagoon of Óbidos are not the only examples where the acoustic classification was unable to relate well to measured characteristics in the bottom. Hutin et al. (2005), showed that the QTC

VIEW Series V failed to reveal benthic biotopes (in an area of the St. Lawrence Estuary, Québec, Canada), namely scallop beds and Riegl and Purkis (2005) revealed that the QTC Series V was able to distinguish between unconsolidated sand and hard bottom but did not identified the coral banks present on the studied area, in the south-eastern Arabian Gulf (United Arab Emirates). Our work however does not support the notion that QTC VIEW Series V gives misleading bottom classification, given that it was used in a mid shelf area off Lisbon, showing the same acoustic pattern as QTC VIEW Series IV for the same area.

Unlike with Series V, several studies have been carried out with the QTC VIEW Series IV and several authors have demonstrated its efficiency for sea bottom classification. Studies done by Collins et al. (1996) in Placentia Bay (east coast of Canada), revealed the ability of the QTC VIEW Series IV system to distinguish habitats suitable for different age classes of the juvenile Atlantic cod, characterized by specific combinations of sediment grain size, bathymetric relief, water depth and the presence/absence of algae. According to Collins and Lacroix (1997), the roughness of the seabed revealed to influence the performance of the QTC VIEW Series IV system. Collins and Galloway (1998), in an area of the inner harbour of Vancouver (Canada), showed that the acoustic diversity successfully captured a high variety of seabed types, based on sediment grain size and the presence/absence of shell debris. Wienberg and Bartholomä (2005) recently confirmed these results with work performed in Weser Estuary (German Bight, southeastern North Sea) and further showed that the occurrence of bedforms also appears to be important for the final acoustic classification. Hamilton et al. (1999) in the Cairns area, Great Barrier Reef, Australia, noted that the texture properties of the sediment, and not only grain-size, could influence the acoustic diversity. Studies conducted by Bornhold et al. (1999) in Southern Gulf Island of British Columbia (Canada), also showed that the QTC VIEW Series IV could reflect the seafloor sediment texture and other properties such as microtopography. Earlier, Collins et al. (1996) argued that microtopography and ripple marks could influence the acoustic echo. Ellingsen et al. (2002) in the Frænfjorden, western Norway, indicated that the acoustic backscatter was influenced by sediment grain size. Recent studies also indicate that the presence/absence of algae, bivalve shells and some benthic species may also influence the single-beam acoustic backscatter. Studies by Smith et al. (2001), for the characterisation of oyster bottoms in Chesapeake Bay, USA, revealed that the acoustic seabed classification systems employed (QTC VIEW Series IV and RoxAnn) differentiated between grain size bottom types (sands to mud) and bottoms with pure shell from those with different portions of sand or mud and shell. Morrison et al. (2001) used the QTC VIEW in Kawau Bay, New Zealand, to detect transition areas between different habitats within soft sediments. Anderson et al. (2002) in Placentia Bay, Canada, showed the ability of the QTC VIEW system to identify eight different marine habitats, some of them characterised by the presence of algae. Von Szalay and McConnaughey (2002) and Hutin et al. (2005), demonstrated that this acoustic response is also influenced by bottom slope.

More or less explicitly, those works indicate that the acoustic classification is particularly responding to physical characteristics of the sediment, namely grain-size. None of the above mentioned studies however were conducted with the QTC VIEW Series IV at the shallower operation limit of the equipment as was the case of the study we conducted at the entrance channel of Ria the Aveiro (Freitas et al., 2005). In fact, even working in a very shallow area (5-15 m depth) the results obtained in this study confirm the sensitivity of the acoustic system to the sediment grain-size characteristics and demonstrate its efficiency to assess and map seabed habitats. The distribution of the superficial sediments in the entrance channel and adjacent near shore shelf represents well the prevailing hydrodynamic forces, with coarse sand and gravel on the navigation channel, medium sand at the entrance and fine sand further outwards on the shelf. The decreasing of the sediment particle size from inside the navigation channel towards the shelf, accompanies the reduction of the current velocity in the same direction (Dias et al., 2000; 2003; Almeida and Dubert, 2003). This grain-size gradient was effectively captured in the acoustic diversity pattern, resulting in a very close agreement between the spatial distribution of the acoustic classes and the sediment pattern. The four acoustic classes corresponded to the three major soft sediments (coarse, medium and fine) and the hard bottom. The acoustic ability to adequately map and monitor the seabed in such a particular area, characterised by intense ship traffic and strong tidal currents, is of relevant importance due to the difficulty of using conventional sediment sampling devices and a stationary vessel in such conditions. Wienberg and Bartholomä (2005) had also demonstrated the high performance of this acoustic system in a similar survey area with navigation channels in the Weser estuary (Germany).

The near shelf off Aveiro is an area characterised by a range of sandy/gravel sediments with low silt and clay content, a smooth slope and with no highly three-dimensional features, such as, bedrock, algae beds and biogenic structures. None of the previous studies applied the acoustic seabed classification system to such type of monotonous area. The results obtained (Freitas et al., 2003a) revealed that, even under such particular conditions, the acoustic pattern showed the same inshore-offshore succession as the environmental and the biological data, identifying the two major benthic biotopes in the area, corresponding to a fine/very fine sand benthic community, located inshore, and a gravely sand benthic community, located offshore. This particular study also indicated that whereas there was agreement between the distribution of the two major acoustic classes and the benthic communities, the third acoustic class, which refines the inshore-offshore gradient through the separation of the fine and very fine sands, showed no immediate relationship to the benthic communities distribution. This separation may however be of biological interest, as benthic samples taken in September 2000, coinciding with the recruitment of the bivalve *Donax cf. semistriatus*, indicated that the density of recruits is much higher in the fine sands compared to the very fine sands. Although the lower recruitment observed in the very fine sand could be depth related, the two sediments present different compactness, which could also represent an important difference for the species. As indicated by other works (Preston et al., 1999; Ellingsen et al., 2002 and Kenny et al., 2003), the sediment compactness could be the reason behind the acoustic distinction shown in this work between the fine and the very fine sands, as measured by the shallower penetration of the grab sampler in the very fine sand compared to the deeper penetration in the fine sand. This could also account for the fact that the acoustic classification was apparently unable to distinguish between the several coarser sediments (medium sand, pebbly sand and sandy gravel), since observations during ground-truth sampling suggest that these sediments presented comparable compactness. This sediment characteristic could namely explain the misclassification of the sediment from site 1 (cf. Figure 31), the only fine sand site with the same acoustic classification as coarser sands. When compared to the other sediment samples classified as fine sand, the sediment sample from site 1 had higher proportion of the fractions with grain-size between 0.250-0.500 mm and 0.125-0.250 mm, rendering it much less compact to the grab sampling device than the other fine sand sediments. Such a difference could explain the fact that the sediment sampler penetration was also deeper in this fine sand than in any of the other sediments with similar median classification.

The survey conducted on the continental shelf off Aveiro from the near shore up to 200 m depth should be regarded as a preliminary approach. Even so, it indicates that the acoustic system is efficient to assess and map seabed habitats on a large spatial scale and full shelf depth range, while keeping the same acoustic survey settings. No previous study, done by others authors, had been carried out in such a wide depth range. This property is particularly important as it ensures that future works can be conducted in areas with different depth surveys, in different moments, and those surveys will be fully compatible and may be merged into a single data set to be used in the same analysis. However, such data merging has limitations, namely in the case of the QTC VIEW Series IV equipment, which was used in this case. This is related to the fact that the equipment requires a reference depth to be included in the survey settings, to which all the data collected is normalised. The deeper the survey depth the longer is the collected echo, even if the bottom type remains the same. By normalising the echo-length to a given depth, the final classification remains independent of a depth factor. More recent versions of the QTC VIEW equipment, the Series V and the new version of the acquisition software for QTC Series IV, handle this situation in a different way, using a standard echo-length procedure, in which the depth compensation is performed after the survey (Preston et al., 2004a; patent application: 2004/0027918). Thus, reference depth should always be stated as one of the equipment settings. The acoustic data from surveys with different reference depth are not directly compatible and should not be analysed together. The spatial distribution of the three acoustic classes obtained for the surveyed area agrees with the sediment pattern described for the same area by Abrantes et al. (1997) and with the spatial distribution of the three benthic macrofauna communities described for this continental shelf area by Moreira et al. (2001). Thus, the information obtained reinforces the validity of the acoustic approach as a meaningful way to assess and detail the spatial distribution of soft bottom benthic biotopes on the full depth range of the continental shelf. Nevertheless, the single acoustic class obtained beyond 100 meters depth poorly represents the detailed variety of superficial sediments described by Abrantes et al. (1997) for this area, which could result from the loss of resolution due to the increase of footprint area with increasing survey depth, although apparently such sediment variety has no counterpart in the benthic communities (Moreira et al., 2001).

A close relationship between the acoustic classes distribution and the sedimentary and benthic community assemblages was also seen in the survey conducted at the mid shelf area off Lisbon (Freitas et al., 2003b). This study area was surveyed with the QTC VIEW Series IV, and a detailed part of the area was also surveyed with the Series V. Unlike what happened in the lagoon of Óbidos, the Series V acoustic pattern clearly identified the spatial distribution of the sedimentary and biological groups obtained for this area. In fact, the results from both acoustic systems were coincident and suggested a soft bottom habitats spatial model in which the sedimentary and the biological affinity groups succeeded along inshore-offshore and shelf-estuary directions. Thus, over the study area, the acoustic pattern was very effective in identifying the superficial sediments gradual fines increase. Following sediment succession, the macrofauna also exhibits a gradual change of the dominant species.

As was demonstrated in this study, Morrison et al. (2001) also showed the ability of the acoustic system QTC VIEW Series IV to distinguish between sand from mud. The results obtained in this survey, as several previous studies demonstrated (e.g. Collins and Galloway, 1998; Ellingsen et al., 2002), also indicate that the acoustic classification is responding to the different bottom types, independently on the depth surveyed.

In the mid shelf surveys, some exceptions were noticed on the overall agreement between the acoustic classes and the prevailing sediment and biological affinity groups. The most important concerns the coarser sediment locally observed in site 13 (cf. Figure 43), also corresponding to a particular biological assemblage dominated by small interstitial annelids. This small area of coarser sediment is probably associated with the stronger drift currents along the western coast, as we leave the protection of the cape located to the north of the study area, and has no corresponding acoustic class. A second apparent exception concerns one of the biological assemblages (B21), which has no direct corresponding group, neither in the sedimentary nor in the acoustic data. This group establishes the transition between the biological assemblages B1 and B22 the later better characterised than B21, given the distribution of the dominant species among the affinity groups. As such, the fact that the detailing of the biological succession presents no counterpart in the sedimentary and the acoustic data should not be regarded as a case of acoustic misclassification. Indeed, the transition group here identified as B21 is not always individualised through data treatment, whereas groups B1 and B22 are consistently recognized in this area, from surveys undertaken since 1994 (Quintino et al., 2001) and both have a sedimentary and an acoustic counterpart. The final exception concerns the QTC VIEW series V survey results. Although the two surveys show an overall very consistent acoustic diversity pattern, within the Series V acoustic class A there are several records classified as class C. These records are not randomly distributed, but rather located close to the outfall branches. Class A was shown to correspond with the distribution of fine sand with very low silt content. Previous surveys have occasionally identified coarser sediment in sites located between the outfall branches (Quintino et al., 2001). Although the acoustic system picked-up differences in that area, these could not be assigned to a new acoustic class, perhaps due to the relative low number of echoes sampled between the branches. Nevertheless, this apparent acoustic misclassification could either reflect the particular sediment heterogeneity close to the outfall branches or even the density differences in the water, associated with the sewage discharge. Density differences in the water interfere with sound propagation and we notice, in this survey, a larger proportion of invalid echoes in this particular area closer to the outfall branches.

The specific validation survey conducted, *a posteriori*, aimed to confirm the results obtained and to clarify the exceptions identified between the agreement of the acoustic classification and the sedimentary and biological patterns. The increase of the number of ground-truth sampling sites from the 20 available in the first assessment to 60, clearly confirmed the soft bottom benthic habitats spatial model previously suggested by the acoustic method (Freitas et al., *in press*). The results from the validation survey confirmed that, to the Northwest part of the study area, there is a relatively small patch characterised by loose coarse clean sand, whereas, to the Southeast, there is a very large area where mud with very high silt and clay content dominates. Between these two areas extend a large relatively homogeneous area of clean fine sand and a narrow belt of silty very fine sand, which supports the characteristic patches of the tubicolous polychaete *Hyalinoecia bilineata* (Quintino et al., 2001) A single or very few sampling sites sustained some of the identified areas. This was the case of the large area located to the Southeast occupied by the mud habitat, which was supported by a single ground-truthed sample, and the narrow transition belt of silty very fine sand, characterised by the tubicolous polychaete, supported by only three ground-truthed samples. At the Northwest extremity, the validation survey confirmed the presence of a coarser sand habitat, which in previous studies was also indicated by a single sample. The fact that these coarser sediments, inhabited by a particular faunal assemblage, have no corresponding acoustic class is probably because the acoustic survey covered a small spatial extent, collecting only a small number of echoes in such sediment type and hence has limited influence in establishing a separate acoustic class. However, those areas are not classified as the surrounding acoustic class A, but appear classified as the acoustic class C, which corresponds to the mud habitat. A similar situation was observed in other part of the survey areas, where also intrusions of the acoustic class C were noticed. In these other cases, the intrusions of the acoustic class C did correspond to heterogeneous sediment identified by the ordination analysis and characterised by higher proportions of both silt/clay and gravel fractions. When compared to the clean fine sand and the silty very fine sand, these other sediments have one common characteristic: they are much less compact, allowing the grab to penetrate deeper in the superficial sediment. Given that the acoustic survey was conducted with an echo sounder operating at 50 kHz, this apparent misclassification could also have resulted from the fact that these two types of quite different grain-size sediment should allow a deeper sound penetration than the more compact fine and very fine sand. This suggests that the misclassification of those sites could be due to sediment compactness, as seen before on the near shore shelf survey off Aveiro, confirming namely Preston et al. (1999) that reported the influence of this sediment characteristic on the acoustic signatures in soft seabed in Vancouver Island, Canada. Also Kenny et al. (2003) highlighted the dependency of the acoustic signal from the sediment porosity. Riegl and Purkis (2005) working with the QTC VIEW Series V, also detected the ability of acoustic system to distinguish between unconsolidated sand and hard bottom.

Despite that particular misclassification, the results from both surveys indicate the high potential for the use of the QTC VIEW single-beam acoustic approach in the identification and mapping of large-scale habitat diversity along the coastal shelf, namely in areas covering broad sediment types, such as the mid shelf off Lisbon. The fact that both approaches (acoustics and sediment point samples) gave very coherent distribution areas for the three major benthic biotopes, reassures the acoustic approach as a reliable method for the detailed identification and mapping of large-scale habitat diversity in the coastal shelf and as it does not follows the overall depth gradient, also indicates the independence of the acoustics from depth.

All the studies presented in this thesis used a post-processing approach, i.e., all acoustic analyses were performed after the survey. The same acoustic system (Series IV only) only may be used in real-time classification, through the comparison of acquired echoes with previous ones, used to produce a catalogue of different acoustic classes, each assigned to a given seabed type. In real-time classification, this comparison is made as the vessel moves along the survey lines. With this strategy, the acoustic approach may be used to search for a particular seafloor feature or biotope without the need for further ground-truth validation, as long as the method gives reliable results. Such reliability was assured by the validation approach followed in the mid shelf area. Real-time benthic biotope surveys using single-beam acoustics have many promising applications, but are at a very early development stage and require future research.

CHAPTER 5 - CONCLUSIONS

5. Conclusions

The results obtained in the presented studies, have shown that the single-beam acoustic ground discrimination system is a very valuable tool for the characterisation and mapping of sublittoral soft bottom benthic biotopes. Only when used in very shallow water coastal area, the lagoon of Óbidos, did the approach reveals some limitations in the identification of the benthic biotopes diversity. In all other applications a very good relationship was found between the acoustic diversity and the ground-truth sedimentary and biological data.

At the entrance channel of Ria de Aveiro and near shore shelf, an area characterised by strong tidal currents and frequent ship traffic, the acoustic diversity could be very close related to the superficial sediment types and hard bottom areas. In this particular environment, where conventional sediment sampling from a stationary vessel using grab is less favourable, the acoustic approach may represent an advantage to study the sediment seascape. Furthermore, because this study area comprises a routinely dredged channel for ship traffic, our work indicates that the acoustic methods could be a valuable tool to monitor the channels and sediment mobility.

The acoustic approach also showed high performance for mapping the sediment biotopes in a relative monotonous bottom area, at the near shore shelf off Aveiro, depth from 5 to 35 m, characterised by a range of grain-size sandy sediments, all with very low silt and clay content. Furthermore, the information acquired in this area revealed that the acoustic classification was able to detect different sediment compactness areas.

The study performed on the continental shelf off Aveiro indicated that the acoustic system may be used over a large depth range, maintaining the same base settings, thus permitting to acquire fully compatible data sets, which can afterwards be merged and analysed together, even if not collected during the same survey. Although further research in this field should be conducted, our findings suggest that the use of a single equipment set-up for the whole coastal shelf depth range (i. e. 20 to 200 m), could result in some loss of resolution, namely due to the fact that the sonar footprint will be larger and larger as depth increases.

The sensitivity of the ground discrimination system to the sediment grain-size was also demonstrated in the survey performed at the mid shelf area off Lisbon. In this survey, the fines content in the superficial sediments change gradually with increasing depth and with increasing proximity to the Tagus estuary. The acoustic classes captured this gradual change and identified the predominant sediment types, namely fine sand with low silt and clay content, silty very fine sand and mud. A close relationship with the benthic communities was also verified.

With this study it was also shown that the information acquired by the two seabed classification systems used (QTC VIEW Series IV and V) was consistent and identified the same benthic biotopes. Such agreement between the two surveys could bring to acoustics a more universal value, as a remote sensing tool to identify and interpret soft bottom heterogeneity. Both results indicate that future work should focus on the apparent sensitivity of the acoustic method to sediment compactness, namely through the use of synoptic dual-frequency surveys, one of which would penetrate less the sediment.

Given these results, we conclude that the seabed classification systems used present high potential for the remote assessment of benthic patchiness, although careful ground-truth will be needed to ensure that the acoustic class splits are sedimentological and biologically relevant. Compared to the spatially discrete grab-based sediment sampling, the acoustic survey approach produces reliable habitat maps over large spatial scales, with considerably less sampling and laboratory effort. Also, the fact that the acoustic systems, collect data almost continuously, allows the detection of seabed discontinuity that could otherwise be missed by point data, obtained through the collection of discrete sediment samples.

Finally, the ground discrimination systems also presented the advantage of being suitable to work in very different survey vessels.

Overall, the studies demonstrated that the acoustic ground discrimination system was able to capture the spatial scales and variability of the different seabed types that characterized the various Portuguese coastal shelf areas analysed.

CHAPTER 6 - REFERENCES

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Annexes

Classification of Biosedimentary Gradients: Coupling Acoustic and Traditional Techniques

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Abstract

Acoustic classification of seabed habitats represents a recent evolution in remote characterisation of the marine landscape. This paper describes an application of this new technology in the study of biosedimentary gradients, by combining underwater acoustic and biological survey techniques.

INTRODUCTION

Traditionally, the assessment of seabed habitat characteristics has relied on intensive grab sampling programmes or diving surveys. This approach is labour intensive, time-consuming and disrupts the structural integrity of the sediment habitat, which may induce the loss of important ecological information (Guigné *et al.*, 1993).

Recent progress in acoustic technologies offers new opportunities to explore and describe the marine environment. Having the ability to combine non-intrusive properties with seascape level assessment, the acoustic classification of seabed habitats is becoming more widely used for the remote characterisation of the sea floor, including marine biological sciences. New instruments, as the one used in the present work (QTC View), are based on processing signals from echo sounders, which, after suitable data treatment, allow the discrimination of different sea floor characteristics (Collins and Galloway, 1998). It has been shown that the diversity of the acoustic response is conditioned by sedimentary properties (grain size), bottom roughness (sedimentary bedforms) and organisms (algae mats) (Simpkin and Collins, 1997; Tsemahman *et al.*, 1997; Collins and Galloway, 1998). Such acoustic techniques have also proved to be effective in the assessment of habitat suitability for the juvenile Atlantic cod and to predict the distribution of the seasonal populations of this species (Collins *et al.*, 1996).

This work applies this new methodology to the study of benthic subtidal biotopes combining acoustic and traditional survey techniques, aiming to show the efficiency of such an approach in the identification and characterisation of gradients in the biosedimentary environment.

METHODOLOGY

Study areas

In order to assess the validity and performance of the combined approach, the research will be conducted in five contrasting coastal regions, namely two areas of the Portuguese shelf and three lagoon systems (Figure 1).

The shelf areas are located off the Tagus estuary and off the Ria of Aveiro, with sampling depths ranging, respectively, from 30 to 60 metres and from 15 to 35 metres. The 3 coastal lagoons (Óbidos, Albufeira and Ria of Aveiro) have sampling depths up to 4, 13 and 20 metres, respectively (Rodrigues and Quintino, 1985; Quintino and Rodrigues, 1986; Moreira *et al.*, 1993).

Overall, the superficial sediments from the study areas provide a wide range of grain sizes, from clean coarse sand to mud. In the shelf areas, sediments vary smoothly while in the lagoons they tend to show sharp separation between sand and mud (Quintino and Rodrigues, 1989).

The benthic communities are well described in all the areas and present clear distribution patterns. In the shelf areas, they present a smooth gradient under the influence of natural environmental factors although the anthropogenic inputs from a domestic outfall may locally force the structure and composition. Such discontinuity in the biological gradient is very fine and will test the sensitivity of the acoustic method. This should give insight into the capability of the method to be used in biomonitoring studies. In the lagoons, there are bottom areas covered by algae and phanerogamae, which may also introduce acoustic diversity into the main benthic gradient (Quintino and Rodrigues, 1989; Moreira, 1991; Moreira *et al.*, 1993).

SEABED CLASSIFICATION

The remote classification of the sea bottom requires an acoustic data acquisition system and a set of algorithms, which analyse the data and may further relate the results of the acoustic classification to physical properties of the sea floor. In this manner, the acoustic pulse generated by an echo sounder travels through the water column and reflects from the seabed water interface and the material in the immediate subsurface. The echo received by the transducer is sent to the QTC View that uses the shape of the first returning echo to characterise the seabed, after which the data are analysed by a series of algorithms. The result of this analysis is a digital characterisation of the echo shape consisting of 166 elements from which, through data treatment (PCA), a reduced description composed of three values (Q1, Q2 and Q3) is obtained, corresponding to the coordinates of each echo in the three first PCA axes. When represented in a 3-D space (Q-space), points from a similar seabed type tend to cluster close to each other, forming a class.

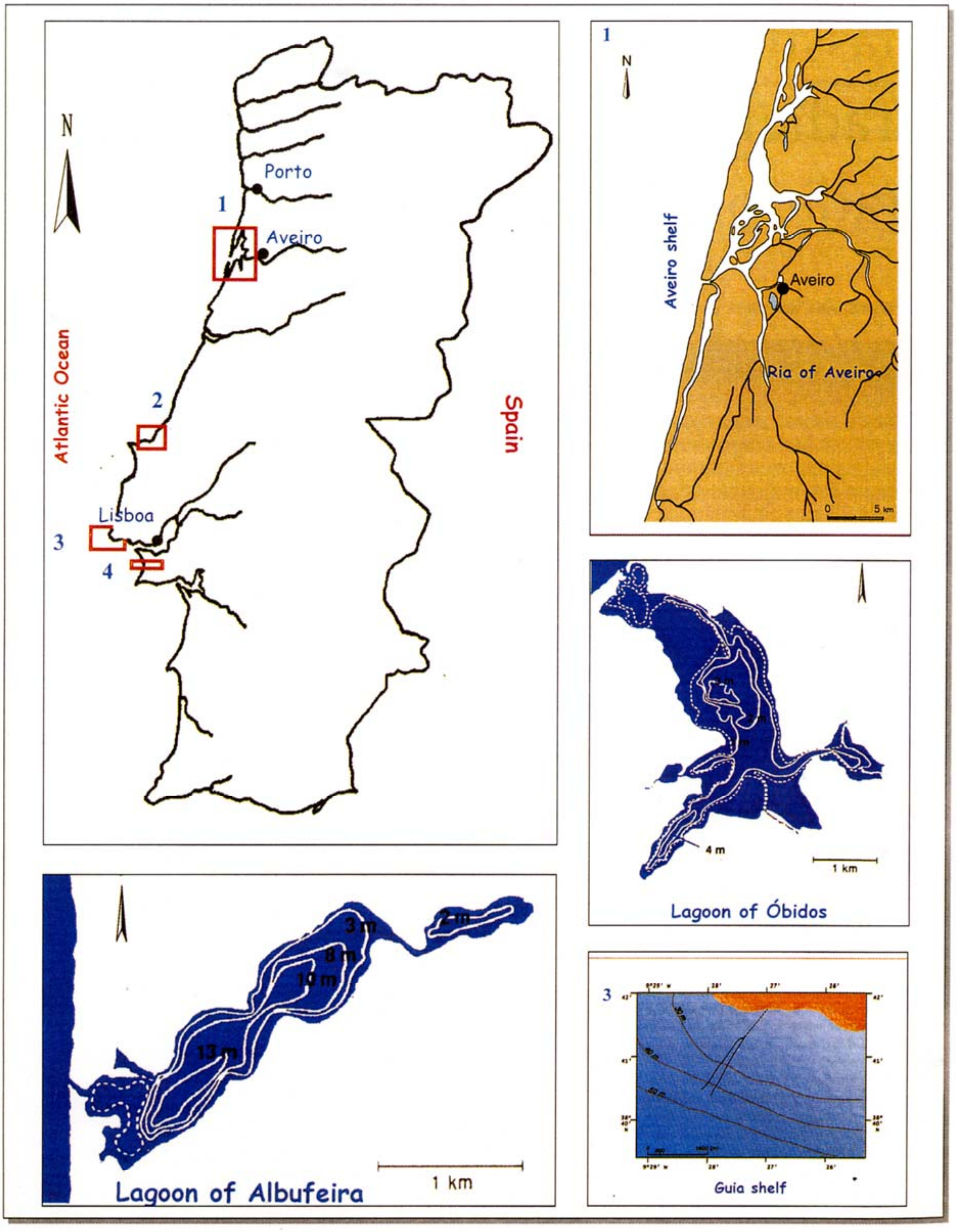


Figure 1
Location of study areas

SURVEY STRATEGY AND DATA TREATMENT

The QTC View system may be used under two survey strategies, depending on the target application and the available ground verification information: supervised and unsupervised classification modes.

Using a supervised classification, a series of echoes are collected from seabeds with known characteristics in order to calibrate the system. Once this phase is completed with the range of the desired signals, a catalogue is built. During posterior surveys, the incoming echoes are assigned to a given catalogue class, with a confidence degree. Ground verification usually takes place during calibration.

Under unsupervised classification, the user collects and stores raw echoes, along the established navigation path, each with a corresponding position fix. This method makes use of post-processing software (QTC Impact) to determine the extent of the acoustic variability in the surveyed seabed. The acoustic data are submitted to cluster analysis (K-means) and classified into a set of acoustic classes. Once this is completed, each acoustic class is further associated with a particular seabed type through ground verification (Collins, 1999). This method was used in the present study.

ACOUSTIC ACQUISITION

During acquisition, the raw waveforms collected by the data acquisition software (QTC View) together with the positioning data from GPS (Global Positioning System), are transmitted to a portable computer for display and post-processing, using the software QTC Impact. The final output from QTC Impact is accepted by GIS software packages (Geographical Information System) (Figure 2), from which charts of the bottom relief and acoustic diversity may be produced, using the co-ordinates (given by the GPS), the depth (given by the echo sounder) and the acoustic classes (identified by the QTC Impact). The acoustic diversity maps obtained may be further used for ground verification analysis.

Some experiments have been made to analyse the characteristics of the acoustic system and survey strategy. This paper presents some of the results obtained in two acoustic surveys carried out in Ria of Aveiro.

GROUND VERIFICATION

Sediment samples for the ground verification studies were collected in four sites along one of the surveyed areas. The sites were chosen after the acoustic classification and at each site photographs were taken to illustrate the sediment characteristics. In future surveys, the structure and composition of benthic macrofauna communities, presence of algae or phanerogamae mats and a range of sediment physical descriptors will also be included in the analysis. Using GIS software, maps of biological parameters and sediment characteristics will be produced and plotted against those obtained for the acoustic diversity.

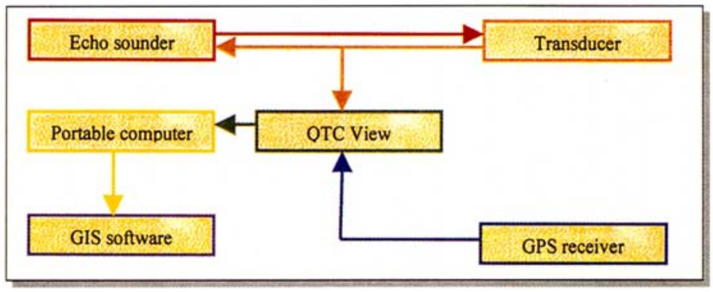
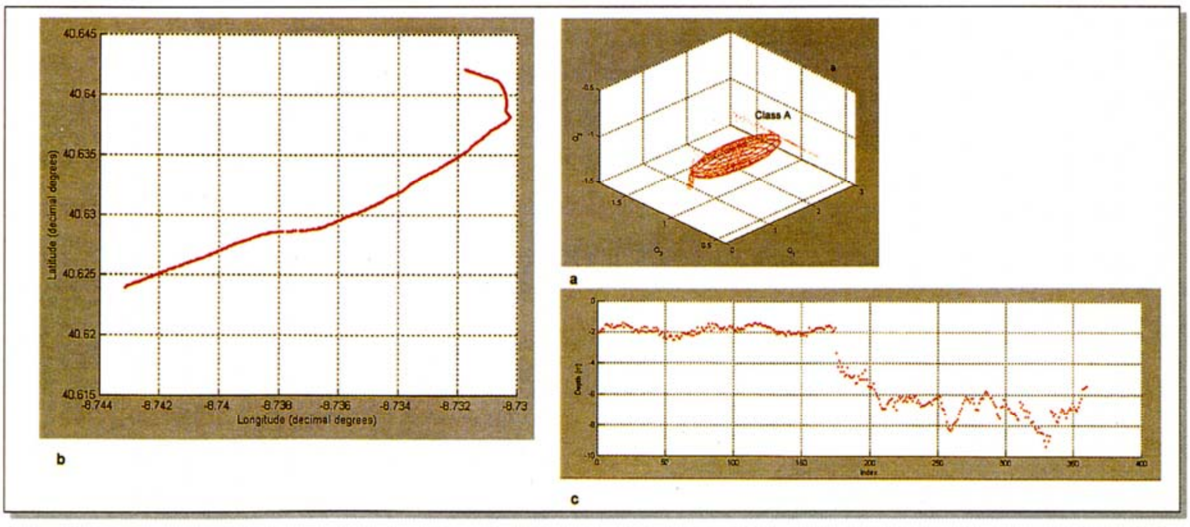


Figure 2
System configuration

RESULTS

The unsupervised classification identified, at each surveyed area, three distinct acoustic classes (A, B and C). Transect 1 (Figures 3, 4 and 5) shows a clear variation of acoustic diversity with depth. Although no sediment samples were collected in this area to evidence this result, previous studies have shown that sediments in this channel vary with depth (unpublished data). We notice different signals for the shallow areas, the slope and the deeper part of the channel. Figures 3 to 5 illustrate how the classification analysis proceeds in the identification of the acoustic diversity, first splitting the whole signal into the shallower and deeper parts (Figures 3 and 4) and finally the slope (Figure 5). The results of this classification approach are acceptable as long as the statistical results of splitting improve the description of the clusters, as illustrated in Table 1. When plotting the number of splits against total score the inflection point of the resulting curve is a strong indication of the optimal split level. Also, the splitting must continue until the class memberships

Figure 3
Acoustic diversity along transect 1. (a) Q-space containing a single acoustic class (class A), before the classification analysis. (b) Navigation path and distribution of the class A along the transect 1. (c) Bathymetric profile along transect 1 with the distribution of the class A



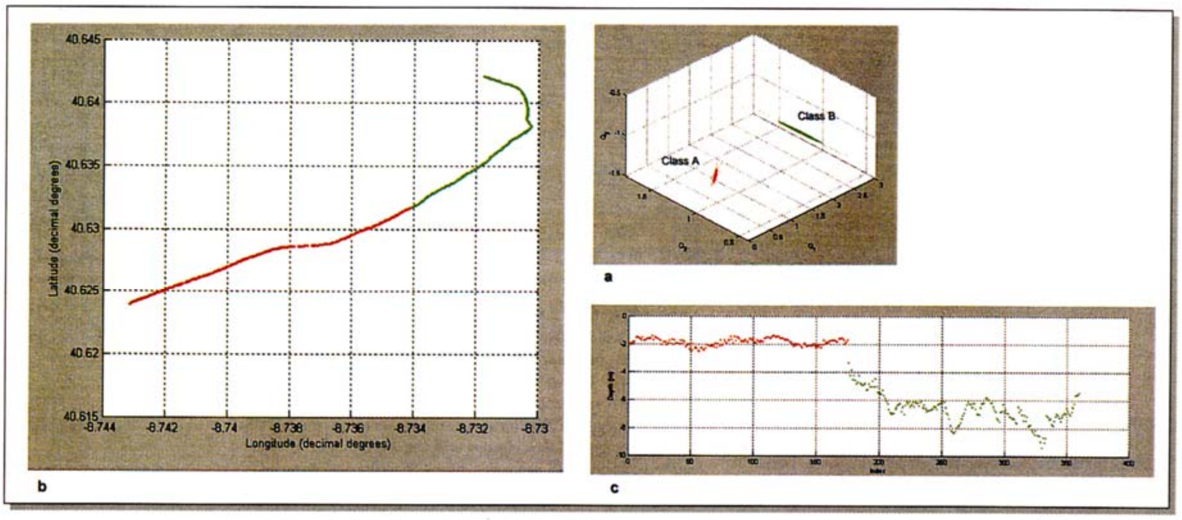


Figure 4 (above)
Acoustic diversity along transect 1. (a) Q-space containing two acoustic classes (class A and class B), after the first splitting of the classification analysis. (b) Navigation path and distribution of classes A and B, along the transect 1. (c) Bathymetric profile along transect 1 with the distribution of two of the different classes (A and B)

become stable and the rate of CPI, defined as CPI (n) = [CPI (n) - CPI (n-1)] / CPI (n-1),tends to be maximum, as shown in Table 1. This suggests that it would be unnecessary to consider a fourth class of acoustic diversity in this data set.

The acoustic diversity identified along transect 2 is shown in Figure 6. Sediment samples were obtained in four sites, corresponding to classes B and C. As seen in the photographs presented in Figure 7, both classes correspond to clean sands with or without shell debris (classes C and B respectively). These were in agreement with the assumption that each site represented by similar seabed type belongs to the same acoustic class. No sediment samples were taken from Class A and so it is not possible to conclude about the sediment type of this class.

CONCLUSIONS

The information obtained from the acoustic classification shows a direct relationship to the physical nature of the sediments. This information indicates that, after careful planning, it will be possible to obtain seabed descriptions from large areas and to translate such information into possible different benthic habitats.

In this way, when compared with traditional methodologies for seabed mapping, acoustic seabed classification provides a cost-effective methodology for the characterisation of the biosedimentary environment and to assess spatial heterogeneity at a much finer scale than in the one acquired from point sampling. Therefore, the information obtained with acoustic techniques and GIS mapping may so provide an excellent starting point to a more directed sampling programme using traditional methods.

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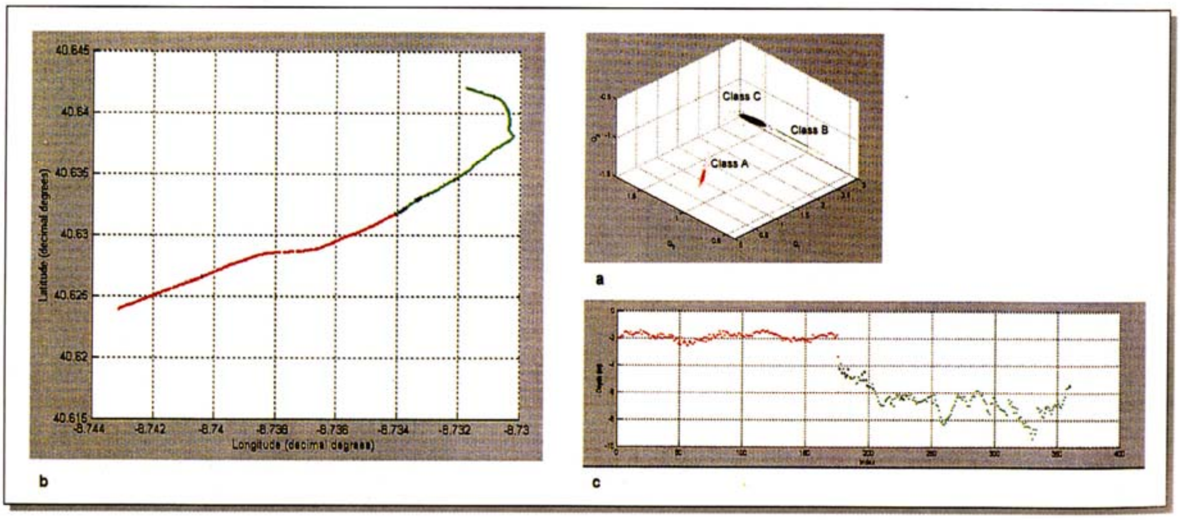

Figure 5 (below)
Acoustic diversity along transect 1. (a) Q-space containing 3 acoustic classes (class A, class B and class C), after the second splitting of the classification analysis . (b) Navigation path and distribution of classes A, B and C, along the transect 1. (c) Bathymetric profile along transect 1 with the distribution of the 3 different classes (A, B and C)

TABLE 1. CLASS STATISTICS

Split	Total Score	CPI	Class	Member	Chi²	Score	CPI rate
1	10955.18			360	30.43	10933	
2	1354.19	28.89		176	1.61	283	
				184	5.82	1071	
3	638.22	74.43		176	1.61	283	1.58
				148	2.20	326	
			C	36	0.81	29	
4	548.59	137.64		176	1.61	283	0.85
				118	1.82	214	
			C	30	0.70	21	
				36	0.83	20	

Table 1 Class statistics
Total score: The sum of the scores of the individual classes. It provides a measure for determining when further cluster splits are no longer justified.
CPI (Cluster Performance Index): Measures the ratio of the distance between cluster centres and the extent of the clusters in Q-space. It is a measure of signal (separation) to noise (cluster variance).
Members: Number of data points, which are members of the class.
Chi²: Measure of clumpiness of each cluster in Q-space.
Score: A product of the number of members and the Chi² value.
CPI rate: [CPI (n) - CPI (n-1)]/CPI (n-1)

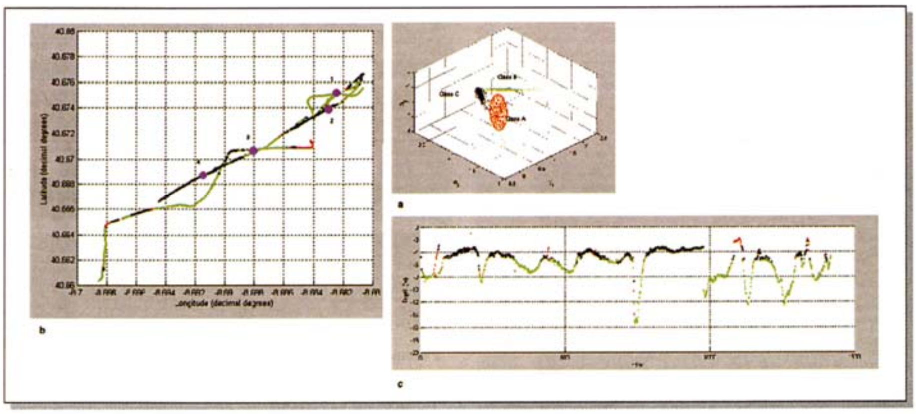

Figure 6
Acoustic diversity along transect 2 (a) Q-space containing three acoustic (AB and C). (b) Navigation path and distribution of classes (AB and C). Sediments were collected at site 1 and 4. (C) Bathymetric profile along transect 2 with the distribution of the acoustic classes

Figure 7 (below)
Photos of sediment taken from the dredged sites. (a) Site 1 - Class B. (b) Site 2 - Class C. (c) Site 3 - Class B. (d) Site 4 - Class C

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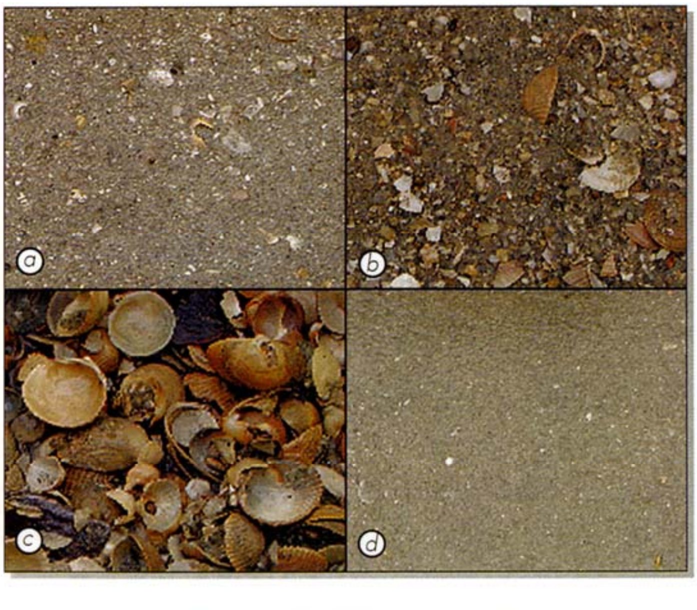

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Acoustic seabed classification of marine habitats: studies in the western coastal-shelf area of Portugal

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Two single-beam, seabed-classification systems, QTC VIEW Series IV and QTC VIEW Series V, were used to identify and map biosedimentary gradients in a mid-shelf area off Western Portugal. The survey area has a moderate slope, a depth ranging from 30 to 90 m along a 3.5-km axis perpendicular to the shoreline, and is characterized by smooth sedimentary and biological gradients. Ground truth for sediment grain size and macrofaunal communities was based on grab sampling at 20 sites. The sedimentary and biological data were analysed using classification and ordination techniques. The acoustic data were analysed with QTC IMPACT software and classified into acoustic classes. The affinity groups obtained in each data set were mapped using a Geographic Information System. All showed good agreement and identified prevailing gradients along a northwest–southeast direction. Three acoustic classes were identified, corresponding to the predominant sediment types, namely fine sand with low silt and clay content, silty, very fine sand, and mud. A close relationship with benthic communities was also verified, although less marked because benthic communities continuously change along the northwest–southeast gradient. Overall, the acoustic system coupled with ground-truthing data was able to discriminate and characterize the various benthic biotopes in the survey area.

Keywords: acoustic seabed classification, benthic biotopes, coastal shelf, habitat mapping, Portugal, QTC VIEW.

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Introduction

Recent progress in acoustic technology offers new opportunities for describing the marine environment. Echosounders and sidescan sonar are commonly used for remote characterization of the seafloor, including, recently, the discrimination of benthic biotopes (Kenny *et al.*, 2003). Tools such as QTC VIEW and RoxAnn process the acoustic signals from single-beam echosounders and output data to Geographic Information Systems (GIS) to map differences in seafloor characteristics (Greenstreet *et al.*, 1997; Hamilton *et al.*, 1999; Kloser *et al.*, 2001; Anderson *et al.*, 2002).

The QTC VIEW Series IV and Series V seabed-classification systems used in this study are powerful tools for the discrimination of marine benthic habitats. Several studies have shown their response to bottom features such as sediment grain size and compactness, seabed roughness, bedrock, benthic organisms, and bottom slope (Collins *et al.*, 1996; Hamilton *et al.*, 1999; Preston *et al.*, 1999; Preston, 2001; Anderson *et al.*, 2002; Ellingsen *et al.*, 2002; von Szalay and McConnaughey, 2002). Most of these studies covered areas with a variety of contrasting bottom features with sharp discontinuities. Recently, their efficiency was assessed in an area of relative seascape monotony, viz. in a sand and gravel, nearshore shelf area, with very low silt content (Freitas *et al.*, 2003). In this present study, both acoustic systems were used in a mid-shelf area with a smooth biological gradient and sediment grain size ranging from clean, fine sand to mud with silt and clay content above 75%, with a view to comparing the results of the QTC VIEW Series IV and Series V systems.

Material and methods

Sampling

The QTC VIEW Series V is an advance in signal acquisition by faster sample digitization and better sample resolution, and dynamic range (Table 1). These have resulted in greater operating water depths and an advanced compensation method for echo-length changes. The Series V acquires and logs the waveform as raw data, in contrast to the pre-processed set of echo descriptors in Series IV. A mid-shelf area approximately 20 km^2 with depth ranging from 30 to 90 m was surveyed in April 2001 using QTC VIEW IV. Survey lines at 500-m spacing were run aboard "N.R.P. Andrómeda" (Figure 1). The QTC VIEW V was used in April 2002 over that part of the area closer to the outfall branches, with the survey lines approximately 100 m apart (see Figure 1), aboard the "N.R.P. Auriga", a twin vessel to "N.R.P. Andrómeda" of similar size, design, and engine size. In both surveys the transducer was fixed to the side of the vessel being used and the speed was close to 6 knots. Positions were confirmed with a Global Positioning System (GPS). Both acoustic systems include a computer for the acquisition, display, and storage of the data collected. Table 2 summarizes the echo-sounder and QTC VIEW base settings for both surveys.

In April 2001, five ground-truth 0.1 m^2 Smith–McIntyre grab samples were taken at each of 20 sites (see Figure 1), two for sediment and three for macrofaunal analysis. These were washed over a 1-mm mesh screen and the remaining material fixed in 4% buffered formalin.

Acoustic classification

QTC VIEW applies a series of algorithms to the shape of the first returning echo, translating it to an array of 166 elements (Collins *et al.*, 1996). Through Principal Component Analysis (PCA), a reduced description comprising three values (Q1, Q2, Q3) is obtained. The Q-values correspond to the first three PCA axes (Collins and McConnaughey, 1998). This matrix was classified using a K-means algorithm, with the software QTC IMPACT v3.00. This non-hierarchical, divisive method promotes a progressive splitting process. At each split, a series of statistical measures are provided, namely the total score and the Cluster Performance Index (CPI) rate. The total score is the sum of scores of the individual classes and the CPI measures the ratio of the distance between cluster centres and the extent of the clusters in the Q-space. They were used as indicators of the optimal split level. Initially, the total score decreases rapidly, and further splits lead to smaller changes in this descriptor. Plotting the number of splits against total score, the inflection point of the resulting curve gives an indication of the optimal split level (QTC, 2002). CPI rate, defined as $CPIr = (CPI(n) - CPI(n-1))/CPI(n-1)$, tends to be maximum at the optimal split level (Kirlin and Dizaji, 2000), and was also used as an indicator of the optimal number of acoustic classes to retain (Freitas *et al.*, 2003). Recently, Legendre *et al.* (2002) proposed a method by which to analyse QTC VIEW data, a method that also combined PCA and K-means but used a different evaluation for the best number of clusters to retain.

Table 1. The QTC VIEW Series IV and V systems compared.

Parameter	Setting: QTC VIEW Series IV	Setting: QTC VIEW Series V
Sample rate	20 kHz	5000 kHz
Resolution	8 bits	12 bits
Dynamic range	60 dB (manual gain)	+80 dB (automatic gain control)
Depth range	10–500 m	0.75–2000 m
Depth compensation	Manual reference depth selection	Automatic standard echo length
Raw data	Feature vectors	Full bipolar waveform, interpolated envelope
GPS input	GGA or GLL, 4800 baud	GGA, GLL, RMC custom unlimited baud
Acoustic classification	Real time and post-processing	Post-processing
Quality assurance/ quality control during acquisition	Off-line waveforms, real-time manual water-depth check	Real-time waveform visualization and depth pick

Laboratory analysis

Sedimentary and biological descriptors for the 20 sites included sediment grain size, total volatile solids, and redox potential and macrofauna species composition and abundance. Grain size was analysed by wet and dry sieving. The silt and clay fraction, i.e. fine particles, with diameters less than 0.063 mm, and the gravel fraction, particles with diameters above 2 mm, were expressed as a percentage of the total sediment (dry weight). The sand fraction (0.063–2.0 mm) was sieved through a battery of meshes to sort the particles into the size ranges given in Table 3. The sediment was classified according to the median value of $\phi = -\log_2$, particle size in mm, and the Wentworth scale (Buchanan, 1984). Total volatile solids were determined by loss on ignition at 450°C (Byers *et al.*, 1978). Redox potential was measured on board at −4 cm from the sediment surface with specific probes (Pearson and Stanley, 1979). The three replicate samples per site for the study of macrofauna were processed individually. In the laboratory, the animals were sorted and identified to the lowest possible taxonomic level, and for each sample a species list with the respective abundance was determined.

Data analysis

For each site, the environmental data matrix includes the seven grain-size classes, the median, the total volatile solids content, and the redox potential. The normalized Euclidean distance was used to produce a [sites × sites]

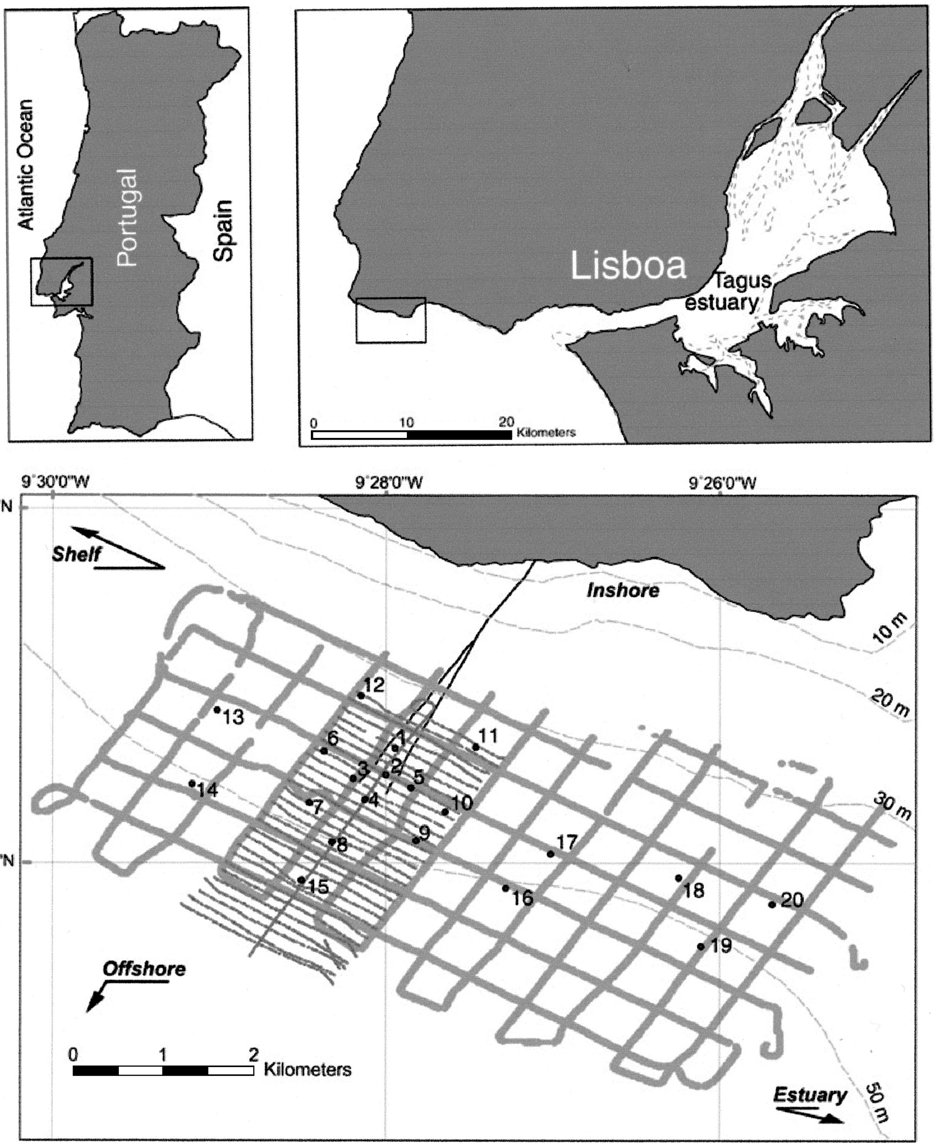

Figure 1. The study area showing the acoustic-survey lines from QTC VIEW Series IV (larger area) and Series V, the 20 sampling sites for the study of benthic communities and superficial sediments along with the sewage-outfall branches.

distance matrix submitted to classification analysis using the average-clustering algorithm and to ordination analysis using non-metric, multidimensional scaling (MDS). Both used the software PRIMER v5 (Clarke and Gorley, 2001).

The biological data were represented by a matrix of 20 sites per 119 variables, corresponding to the species abundances. After square-root transformation, the [sites × sites] Bray–Curtis similarity matrix was classified with the average-clustering algorithm. Ordination was done by correspondence analysis using the software MVSP v3.12d (Kovach, 1999).

The classification output files representing the acoustic diversity were analysed in ARC VIEW 8.1. For this, the final output files from both surveys were opened separately in a spreadsheet and the echo description, latitude and longitude, class name, class confidence, and class probability were selected from the appropriate fields. The data were sorted first by confidence level, and those under 98% were deleted. The confidence value is the probability that a record belongs to the class to which it has been assigned, rather than to any other class. Based on Bayes' theorem, this value is a measure of the covariance-weighted distances between the position of the record in Q-space and the positions of all cluster centres (QTC, 2002). The resulting file was further sorted by the probability and values under 1% were ignored. The probability value of

Table 2. Survey base-settings for both echosounders and acoustic systems. (AGC, automatic gain control.)

		Setting	
	Parameter	QTC VIEW Series IV (NRP Andrómeda)	QTC VIEW Series V (NRP Auriga)
Echo sounder	Beam width	44°	19°
	Transmit power	150 W	100 W
	Pulse duration	625 µs	300 µs
	Ping rate	5 per s	5 per s
	Frequency	50 kHz	50 kHz
QTC VIEW	Base gain	5 dB	AGC

a record is based on the position of that record in the Q-space and the characteristics of the class to which it has been assigned. This is a measure of the closeness of the record to the cluster centre, weighted by the covariance of the cluster in the direction of the record. Probability and confidence calculations are based on Bayes' theorem and the assumption that the underlying distribution in Q-space is Gaussian (QTC, 2002). The acoustic, sediment, and macrofauna plots were overlapped to facilitate comparison.

Results

Sedimentary gradients

The classification and ordination analysis of the environmental data is displayed in Figure 2, and a summary

Table 3. The mean values for the sedimentary data in each of the affinity groups identified by classification and ordination analysis.

	Groups			
	A	B1	B2	C
Sampling sites	13	1–12,14, 17,18	15,16,20	19
Total volatile solids (%)	0.73	1.05	2.33	5.48
Redox potential (mV)	390.50	129.70	79.20	−7.50
Gravel (%)				
>2.0 mm	0.13	0.31	0.63	0.03
1.0–2.0 mm	3.77	0.76	0.53	0.08
0.5–1.0 mm	25.86	2.25	0.53	0.18
0.25–0.5 mm	37.00	4.92	0.77	0.27
Sand (%)				
0.125–0.25 mm	23.01	65.68	37.57	2.90
0.063–0.125 mm	9.30	23.76	40.70	15.33
Fines (%)				
<0.063 mm	0.94	2.37	19.36	81.26
Median (Φ)	1.55	2.68	3.20	>4.00
Sediment classification	Medium sand	Fine sand	Silty very fine sand	Mud

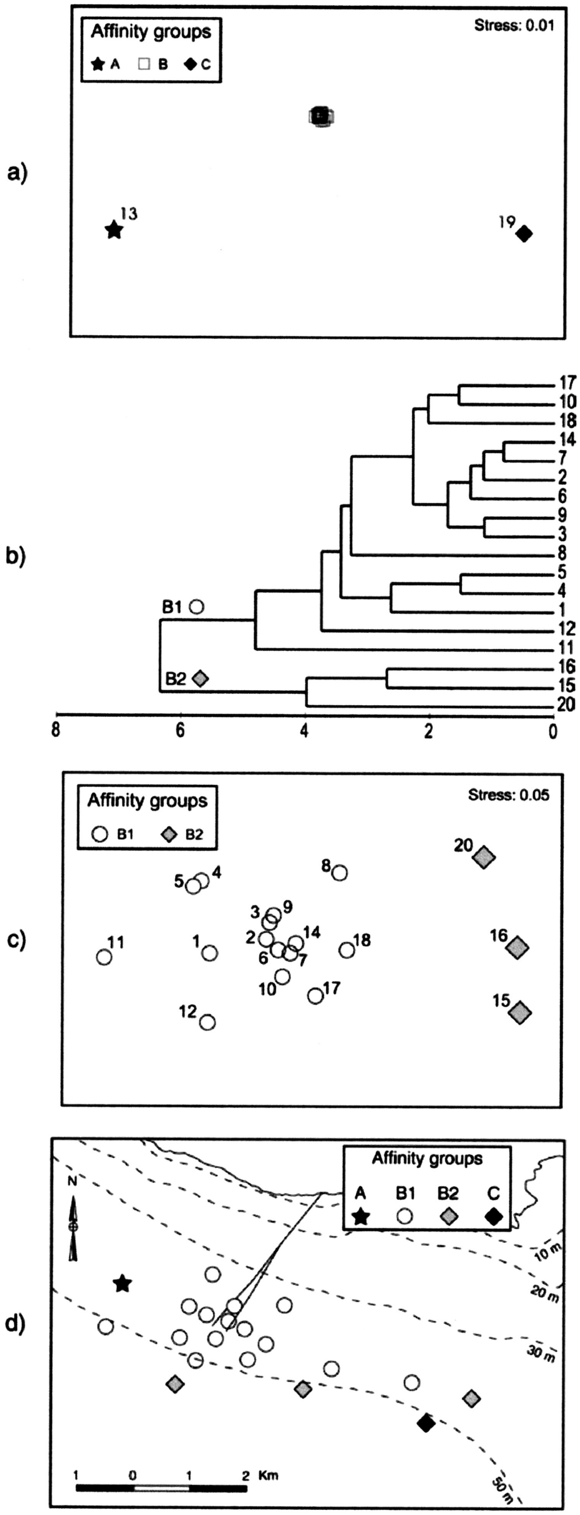

Figure 2. Sedimentary affinity groups (A, B1, B2, and C) identified among the sampling sites. (a) MDS with all sampling sites; (b) classification analysis, excluding sites 13 and 19; (c) MDS excluding sites 13 and 19; and (d) spatial distribution of the affinity groups.

characterization of each group is given in Table 3. When including all the sampling sites in the analysis, three groups were separated in the ordination diagram (Figure 2a): group A (site 13), group C (site 19), and group B (the remaining sites). Sites 13 and 19 over-dominate the ordination pattern because of their particular grain size. The coarser sediment was observed at site 13, the only site classified as medium sand, and site 19 had a silt/clay fraction much higher than elsewhere (Table 3). Excluding these two sites from the analysis, group B is further subdivided into subgroups B1 and B2, as shown in the classification and ordination diagrams (Figure 2b, c). The spatial distribution of the major affinity groups (A, B1, B2, C) is shown in Figure 2d. Along the axis A → B1 → B2 → C, the superficial sediments show gradual increases in the median value, the silt and clay content, and the total volatile solids, while the redox potential decreases (Table 3). Most of the superficial sediments in the study area correspond to fine sand with low silt and clay content (subgroup B1). With increasing depth (inshore–offshore axis, cf. Figure 1) and towards the estuary (shelf–estuary axis, cf. Figure 1), the superficial sediment becomes silty, very fine sand (subgroup B2), and finally mud (group C) (cf. Table 3).

Biological gradients

The ordination and classification diagrams of the biological data are shown in Figure 3. Sites 13 (Group A) and 19 (Group C) tend to over-dominate the ordination pattern (Figure 3a), as seen previously with the sedimentary data. Excluding them, the analyses show the subdivision of Group B into B1 and B2, and a further split into B21 and B22 (Figure 3b, c). Their distribution in plane 1–2 of the correspondence analysis (Figure 3c) indicates continuous change rather than sharp discontinuities between the groups. This is confirmed in Table 4, where the species succession along the biological gradient and the mean species richness and abundance in each affinity group are summarized.

The spatial distribution of the benthic-affinity groups identifies the same dominant patterns along the inshore–offshore and shelf–estuary directions as observed in the spread of the sedimentary gradient (Figure 3d). This pattern has been consistently reported in this coastal region in the period 1994–1998 (Quintino *et al.*, 2001). The succession represented by groups A → B1 → B21 → B22 → C is similar to that obtained with the sedimentary data (Figure 2d). At the northwest extremity, site 13 (group A) is characterized by interstitial polychaetes (Table 4). At the southeast extremity, site 19 (group C) is characterized by faunal impoverishment (Table 4) due to the high fines content and chronic hydrocarbon contamination of the superficial sediments (Quintino *et al.*, 2001). Between these two groups, the faunal succession corresponds to a gradual replacement of the dominant species (Table 4). Apart from site 19, the overall tendency along this succession is a slight increase in both species richness and abundance. Within the succession, the subgroup B21, spatially located between B1 and B22 (Figure 3d), is the less well characterized, with the smaller number of dominant species. This agrees with its position in the ordination, i.e. closer to the origin and between B1 and B22 (Figure 3c).

Acoustic gradients

The results of the acoustic classification by both QTC VIEW systems are given in Table 5. In both cases the optimal-classification solution corresponds to three acoustic classes, A, B, and C. These classes were obtained at the second split, when total score tended to stabilize (QTC VIEW Series IV) or reached the minimum value (QTC VIEW Series V), and the CPI rate was at the maximum value (Table 5). The acoustic pattern identified in both surveys is similar (Figure 4). The acoustic classes from the Series IV survey change along the inshore–offshore and shelf–estuary directions. Those of the Series V survey detail the inshore–offshore succession using a finer spatial grid.

The joint geographical distribution of the acoustic classes and the sedimentary and biological affinity groups, shown in Figure 5, indicates close correspondence between the acoustic patterns and the main sedimentary and biological assemblages. Acoustic class A is predominant in the survey area and corresponds to the region occupied by fine sand with low silt content (sedimentary group B1, Figure 5a, and Table 3; biological group B1, Figure 5b, and Table 4). Acoustic class B corresponds well with the area of silty, very fine sand (sedimentary group B2, Figure 5a, and Table 3; biological group B22, Figure 5b, and Table 4). Finally, acoustic class C corresponds to the area of mud with high silt content (sedimentary group C, Figure 5a, and Table 3; biological group C, Figure 5b, and Table 4). A single ground-truth sample was taken inside acoustic class C (site 19). During a recent survey (October 2002, unpublished data), several other samples were taken within this area, confirming that the superficial sediment is similar to that described in this article for site 19.

Discussion

Using acoustic methods, Collins *et al.* (1996) were able to distinguish habitats suitable for different age classes of juvenile Atlantic cod, habitats characterized by specific combinations of sediment grain size, bathymetric relief, water depth, and the presence or absence of algae. Collins and Galloway (1998) showed that acoustic diversity successfully captured a high variety of seabed types based on sediment grain size and the presence or absence of shell debris. Preston *et al.* (1999) reported comparable results, showing that sediment porosity and grain size influence the

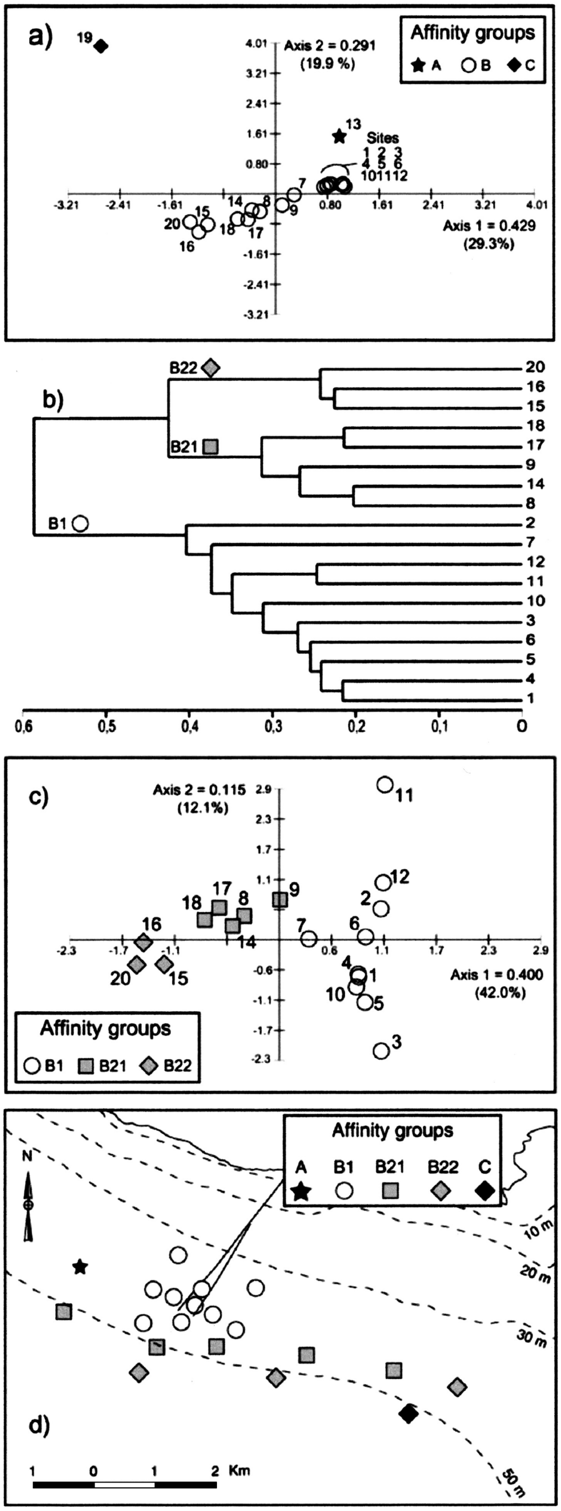

Figure 3. Biological affinity groups (A, B1, B21, B22, and C) identified among sampling sites. (a) Correspondence analysis with all sampling sites; (b) classification analysis, excluding sites 13 and 19; (c) correspondence analysis, excluding sites 13 and 19; and (d) spatial distribution of the affinity groups.

Table 4. The biological succession in the affinity groups obtained by classification and ordination analysis. The taxa are represented by their mean abundance per unit sample (0.1 m^2) and include only the species whose abundance per site is higher than 3% of the site total. Highlighted values indicate the highest mean abundances by group.

	Groups				
	A	B1	B21	B22	C
Sampling sites	13	1–7, 10–12	8,9,14, 17,18	15,16,20	19
Mean abundance (A/0.1 m^2)	96.7	102.1	143.1	243.4	109.3
Mean species richness (S/0.3 m^2)	38.0	41.3	46.0	52.0	31.0
Mean species richness (S/0.1 m^2)	16.3	25.0	26.9	33.5	19.0
Species succession					
Pisione remota	72.0				
Glycera oxycephala	9.0				2.0
Mediomastus capensis	50.0	4.7	0.8	1.0	
Atylus falcatus	3.0	2.6			
Spionidae n. det.	10.0	0.4	2.4	1.7	
Tellina fabula	18.0	41.3	5.0		
Chaetozone setosa	52.0	61.0	2.2		
Urothoe pulchella	1.0	6.2	0.8	0.7	
Capitella spp.		27.3			
Aora typica		0.8			
Mactra corallina		9.3	1.8		
Sigalion mathildae		2.8	1.2		
Mysella bidentata		7.8	7.4	4.3	
Atylus swammerdami		4.0	3.4	0.3	
Anomura n. det.		4.7	3.0	2.0	
Photis longicaudata		8.2	1.8	3.0	
Glycera tridactyla	1.0	5.4	4.8	3.0	3.0
Spio decoratus	1.0	4.2	1.6	1.7	
Nassarius reticulatus	3.0	15.0	2.0	4.7	
Ampelisca brevicornis		5.0	3.0	3.0	2.0
Sabellaria alveolata		7.2		0.3	
Magellona filiformis	8.0	4.7	67.6	0.3	
Paraonidae n. det.	3.0	6.8	10.2	4.0	10.0
Aoridae n. det.	3.0	0.3	7.8	3.0	
Spiophanes bombix	1.0	6.8	23.0	10.0	
Hyalinoecia bilineata	8.0	11.3	89.6	125.7	
Prionospio spp.	5.0	11.4	31.0	32.0	4.0
Ampelisca spp.	1.0	1.6	13.2	40.3	24.0
Nucula spA		0.8	2.4	12.0	1.0
Tellina pulchella		0.3	1.6	28.3	1.0
Maldanidae spA		0.2	10.8	150.7	
Spiophanes kroeyeri		0.4	9.4	31.7	6.0
Lumbrinereis cf. *latrelli*		1.9	69.8	98.3	80.0
Chaetopteridae n. det.		0.1	0.2	17.7	1.0
Abra alba		2.7	1.2	19.0	2.0
Thyasira flexuosa			3.8	23.0	16.0
Maldanidae spB			0.2	18.0	
Terebellidae n. det.		0.9	0.2	1.0	46.0
Hydrobia ulvae					17.0
Thyasira spA					19.0

acoustic response. Hamilton *et al.* (1999) found that the bottom classes suggested by the acoustic system had consistent grain size and texture properties and followed grain-size trends. The work of Ellingsen *et al.* (2002) showed

Table 5. Classification statistics for the QTC VIEW surveys.

System	Split	Total score	CPI	Class	Members	Chi^2	Score	CPI rate
QTC View Series 4	0	246178.28	–	–	15517	15.87	246178	–
	1	178679.63	1.43	A	9704	16.62	161294	–
				B	5813	2.99	17386	
	2	88535.14	5.42	A	5498	4.90	26916	2.79
				B	4751	9.21	43741	
				C	5268	3.39	17878	
	3	85539.83	13.61	A	4829	8.84	42695	1.51
				B	4243	6.61	28060	
				C	3345	2.66	8906	
				D	3100	1.90	5879	
QTC View Series 5	0	17216.63	–	–	3921	4.39	17217	–
	1	11105.64	1.04	A	2456	4.02	9870	–
				B	1465	0.84	1236	
	2	5119.34	4.06	A	1551	1.09	1692	2.90
				B	1259	1.37	1726	
				C	1111	1.53	1701	
	3	6625.07	10.29	A	1100	2.09	2304	1.53
				B	916	1.14	1043	
				C	949	0.81	770	
				D	956	2.62	2508	

Total score = sum of the scores of the individual classes; CPI = cluster performance index; members = number of data in each class; Chi^2 = measure of clumpiness of each cluster in Q-space; score = members × Chi^2; $CPIr = [CPI(n) - CPI(n-1)]/CPI(n-1)$, where n is the split number (see text).

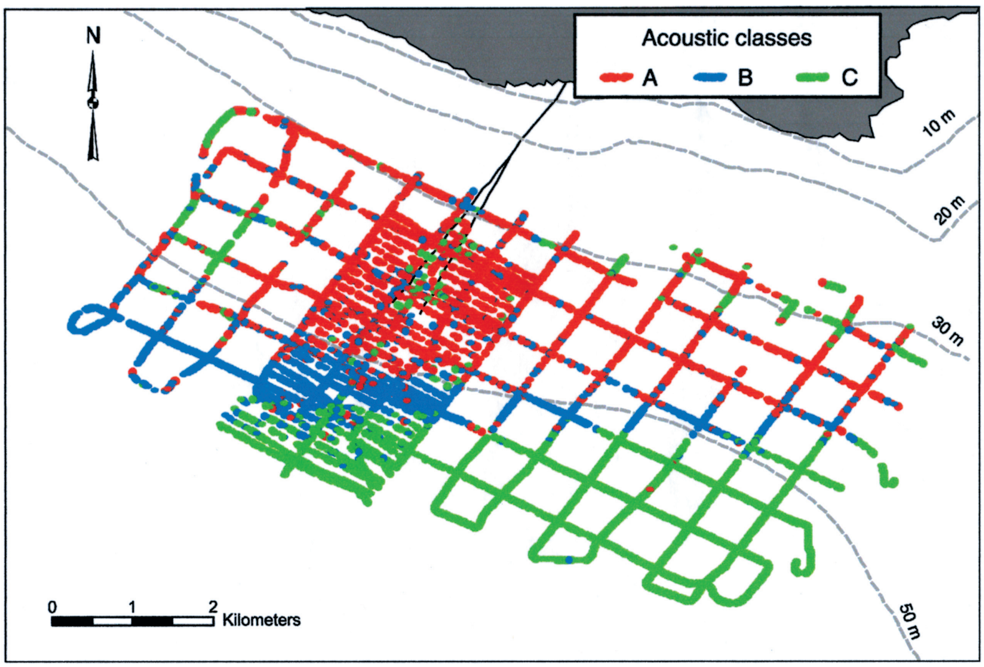

Figure 4. GIS mapping of the acoustic classes A, B, and C identified with the QTC VIEW Series IV (larger area) and Series V (smaller area, closer to the outfall branches).

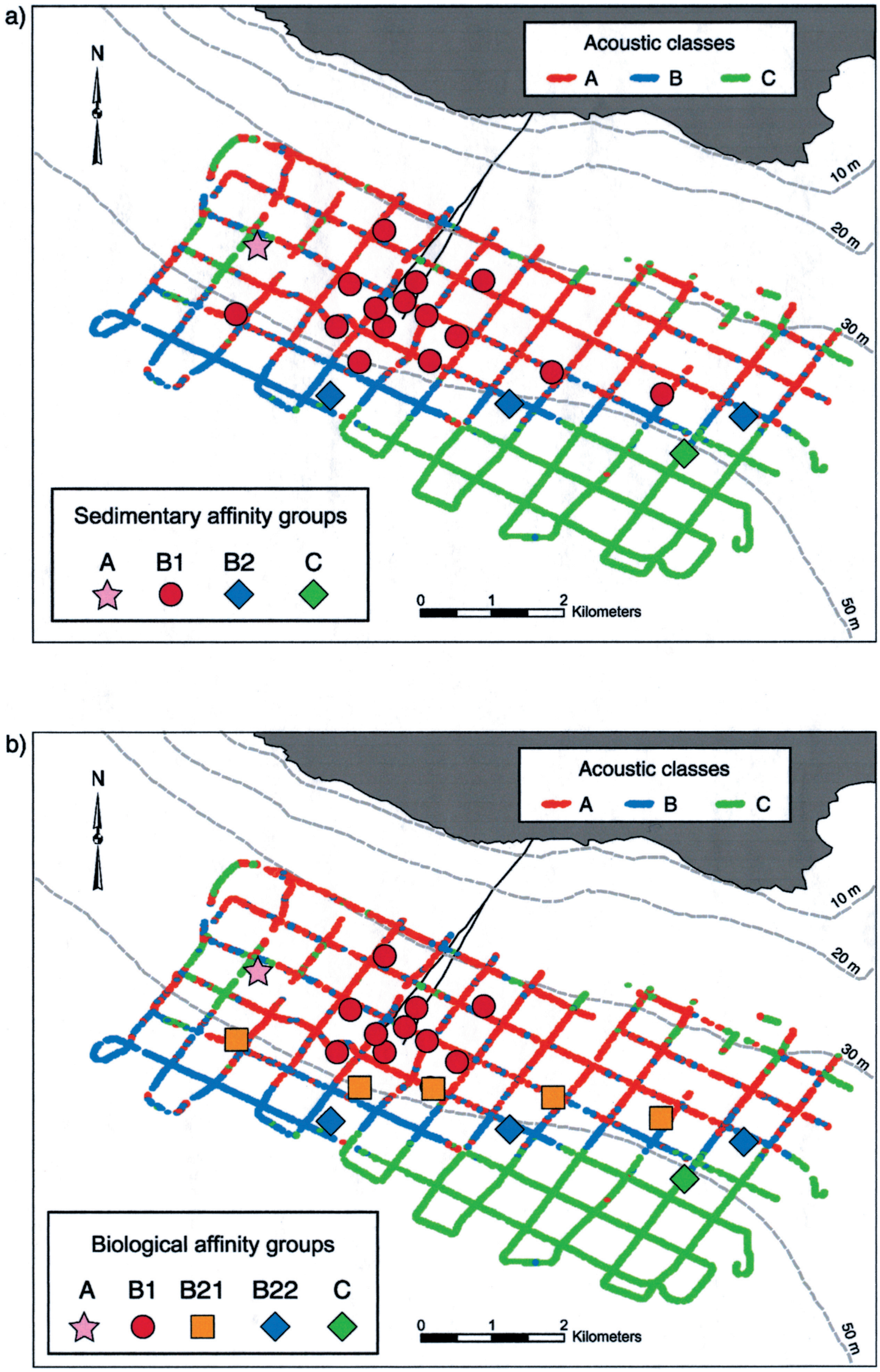

Figure 5. GIS representation of the acoustic classes A, B, and C, jointly displayed with the (a) sedimentary affinity groups and (b) the biological affinity groups.

that the acoustic variety was generally in accordance with sediment grain size. In an area on the Portuguese coastal shelf dominated by a range of sandy sediments, all with very low silt and clay content, Freitas *et al.* (2003) showed close agreement between sediment grain size and the acoustic variability.

All these applications show that the QTC VIEW seabed-classification system is responsive to sediment grain size. The present study agrees with this finding. In fact, the spatial distribution of our three acoustic classes, A, B, and C, follows the same pattern as the sedimentary and biological descriptors, along inshore–offshore and shelf–estuary directions. Class A, to the northwest, corresponds to fine sand with low silt and clay content, and class C, to the southeast, to mud with silt and clay content above 75%. Class B, located between classes A and C, corresponds neatly with the distribution of the silty, very fine sand. The acoustic pattern was thus effective in identifying gradual fines increase of the superficial sediments. Following this sediment succession, the macrofauna exhibit a gradual change of the dominant species.

Some exceptions were noticed in the overall agreement between the acoustic classes and the prevailing sediment and biological affinity groups. The most important concerns the coarser sediment locally observed at site 13, corresponding to a particular biological assemblage dominated by small interstitial annelids. This area has no corresponding acoustic class. A recent sedimentary survey (October 2002, unpublished data), confirmed that there is a coarser sediment area extending westward of site 13. This coarser sediment is probably associated with the stronger currents along the western coast, as the protection of the cape located to the north of the study area is left (Figure 1). This apparent lack of correspondence could be due to the fact that the area of coarser sediment is of small spatial extent and hence has limited influence in establishing a separate acoustic class. The second apparent exception concerns the biological assemblage B21, which does not have a direct corresponding group, either in the sedimentary or in the acoustic data (Figure 5). This group establishes the transition between the biological assemblages B1 and B22 (Figure 5b), better characterized than B21, given the distribution of the dominant species among the affinity groups (Table 4). As such, the fact that the detailed biological succession has no counterpart in the sedimentary and the acoustic data should not be regarded as a case of acoustic misclassification. In fact, the transition group identified as B21 is not always detected through data treatment, whereas groups B1 and B22 are recognized consistently in this area in surveys undertaken since 1994 (Quintino *et al.*, 2001).

The final exception concerns the QTC VIEW Series V survey results. Although the two surveys show a consistent acoustic-diversity pattern overall, within the Series V class A there are several records classified as class C. These records are not randomly distributed but rather located close to the outfall branches (Figure 4). The acoustic class A was shown to correspond with the distribution of fine sand with very low silt content. Previous surveys have occasionally identified coarser sediment in sites located between the outfall branches (Quintino *et al.*, 2001). This was recently confirmed with a finer spatial sampling grid (October 2002, unpublished data). Although the acoustic system detected differences in that area (Figure 4), these could not be assigned to a new acoustic class, perhaps as a result of the relatively low number of echoes sampled between the branches.

Given these results, we conclude that both seabed-classification systems present high potential for the remote assessment of benthic patchiness, although ground truth will be needed to interpret the acoustic classifications. It was also shown that the information acquired by the two seabed-classification systems was consistent using different equipment and different base settings, and identified the same benthic biotopes. Such agreement between two surveys taken a year apart, April 2001 and April 2002, supports the idea that a more general application of acoustics as a remote-sensing tool to identify and interpret soft-bottom heterogeneity is possible.

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Benthic biotopes remote sensing using acoustics

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Abstract

The present work applies novel methodologies to the study of sublittoral benthic biotopes, by combining the information given by underwater acoustic and biological survey techniques. The acoustic seabed classification system QTC VIEW™ was used to map the acoustic diversity between 5 and 40 m water depth on the shelf off "Ria de Aveiro", Western coast of Portugal. Ground-truth was undertaken using an analysis of superficial sediments grain-size, and compared to the species composition and distribution of macrofaunal communities. Sedimentary and biological data were submitted to ordination analysis, and the acoustic data to both ordination and cluster analysis. The acoustic classes identified were mapped using a geographical information system.

The acoustic results showed a very clear geographic pattern, with the acoustic classification being coincident where survey lines crossed, confirming the stability of the classification procedure. At the optimal splitting level, three acoustic classes were obtained. These classes were correlated to differences in coarse, fine and very fine sands. Additional real bottom differences in the grain-size of the coarser sand classes were not detected by the acoustic method, possibly due to the fact that they showed a similar degree of compactness. The benthic ecological data suggests only two main communities, which correspond to the outcomes of a two-class acoustic split. Therefore, a mismatch was noticed between the optimal acoustic split and the number of major biological communities present. However, by dropping the acoustic solution down to two classes, an optimal relationship to benthic communities is achieved. Overall, results suggest that the acoustic system provides very valuable and important data for mapping soft sediment biotopes, even in areas of relative bottom monotony such as the one analysed, but careful ground-truth is required to ensure that the acoustic class splits are biologically relevant.

Keywords: Acoustic seabed classification; Benthic biotopes; Sediment grain-size; Seascape habitat mapping; Coastal shelf; Portugal

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1. Introduction

Considerable effort has been devoted in recent years to the remote characterisation of seabed habitats. For a long time, researchers have known that the acoustic record from echo sounders is indicative of the nature of the seafloor. During the 1920s, the first single-beam echo sounders were developed and, for many years, marine researchers have used these systems to classify the seabed. Classifications were inferred from the echo intensity and by echo comparison through visual examination of the analogue records (Simpkin and Collins, 1997). Because analyses were highly dependent on individual interpretation, they were subjective and inefficient.

Sidescan sonar was developed during World War II for mine hunting, and has become an important tool in marine research. Since the 1960s, this acoustic system has proved to be extremely useful for the identification of underwater structures and seafloor topography and, as a mapping tool, it allows a broad view of different types of sediments (Fish and Carr, 1990; Morang et al., 1997). This has been applied to the mapping of benthic habitats (Service and Magorrian, 1997; Bornhold et al., 1999; Brown et al., 2002).

Seabed classification, using attributes of the echo sounder record such as amplitude and energy content, was initially undertaken in the early 1970s (Simpkin and Collins, 1997). In the late 1980s and 1990s, research focused on the characterisation of the seabed echo. New instruments such as RoxAnn and QTC VIEW™ were developed, allowing detailed discrimination of echoes returned from different bottom features (Collins, 1996; Collins et al., 1996; Greenstreet et al., 1997; MacDougall and Black, 1999). It has been suggested/shown that sediment grain size, sediment compactness and seabed roughness, as well as bedforms such as ripple marks, bedrock outcropping textures, and the presence of bivalve shells and algae, may influence the seabed echo properties (Collins and Galloway, 1998; Hamilton et al., 1999; Preston, 2001; Preston et al., 1999; Cholwek et al., 2000; Kloser et al., 2001; Smith et al., 2001; Anderson et al., 2002; Ellingsen et al., 2002). Benthic species living in the sediment may also determine the acoustic response, thus widening the potential application of seabed acoustic classification (Self et al., 2001). However, factors not related to sediment characteristics may also influence the acoustic classification. Bottom slopes in excess of 5–8° may greatly affect the acoustic responses (von Szalay and McConnaughey, 2002). While some acoustic systems may be influenced by boat speed, or even when acquiring data with the vessel stationary through changing noise levels (Hamilton et al., 1999), others may be indifferent to survey speeds up to 10–12 knots (von Szalay and McConnaughey, 2002). Such findings suggest that further sensitivity studies need to be undertaken before seabed acoustic classification is routinely applied.

This work aims to identify and map the sublittoral benthic biotopes from a shallow coastal shelf area, based on the analysis and interpretation of a single-beam seabed echo combined with sediment and benthic animal sampling. The study area covers approximately 500 km^2 off Aveiro, on the western coast of Portugal, with water depths ranging from 5 to 40 m. The bathymetry follows a gentle slope, with no highly three-dimensional features such as bedrock, algal beds and biogenic structures being present.

2. Methods

2.1. Field sampling

The acoustic survey was conducted with the seabed classification system QTC VIEW, series IV, using a 50-kHz echo sounder. The acoustic system includes a laptop computer, for data acquisition, display and storage. A Global Position System (GPS) provides position, allowing data to be post-processed in a Geographic Information System (GIS).

Pulse duration, power and system gain were varied over sites differing in sediment properties and depth while the vessel was stationary. A configuration was chosen so that useable echoes were received over the full survey area, without clipping, or too low energy level. The final echo sounder and QTC VIEW settings are given in Table 1. Raw echoes obtained at several sites were visualized in real time, to assess possible inference from the operating environment, such as noise from other equipment and from the survey vessel. To minimize such potential noise, the acoustic system was run with an autonomous power source and all other vessel sounders were turned off during the survey.

The acoustic survey was run over 8 days between January and March 2002, aboard the vessel "Ciclone", at an average speed of 6 knots. The survey grid is shown in Fig. 1. A total of 13 lines with length between 7 and 12 km were oriented east to west and placed 3.5 km apart to cover the study area. For quality assurance, six lines, approximately 50 km long, were placed perpendicular to the previous ones (Fig. 1).

Ground truthing was undertaken, using a 0.1-m^2 Smith–McIntyre grab. Sediment samples were taken at 43 sites, at the end of March, just before the end of the acoustic survey (Fig. 1), positioned to cover as much as possible the whole range of acoustic classes identified in the survey. Most were intentionally positioned on the acoustic survey lines (cf. Fig. 1). Data on macrofaunal communities was collected from 14 sites (three grab replicates per site), taken prior to the acoustic survey, in June 2001 (letters A to N in Fig. 1). The sampling sites for the study of the benthic communities coincide with those for the sediment grain-size analysis, with the exception of sites A, F and J (cf. Fig. 1). For these, the granulometric data was obtained on a previous survey, in June 2001. All of the grab samples were collected using the research vessel "N.R.P. Auriga". Grab sampling was limited by sea state and the size of "N.R.P. Auriga" to waters deeper than 10 m, with the exception of one site (39). The smaller and more

Table 1
Survey base settings for the echo sounder and the QTC VIEW series IV

	Parameter	Setting
Echo sounder	Pulse duration	360 μs
	Beam width	44°
	Transmit power	150 W
	Range	40 m
	Ping rate	5/s
QTC VIEW	Base gain	15 dB
	Reference depth	25 m

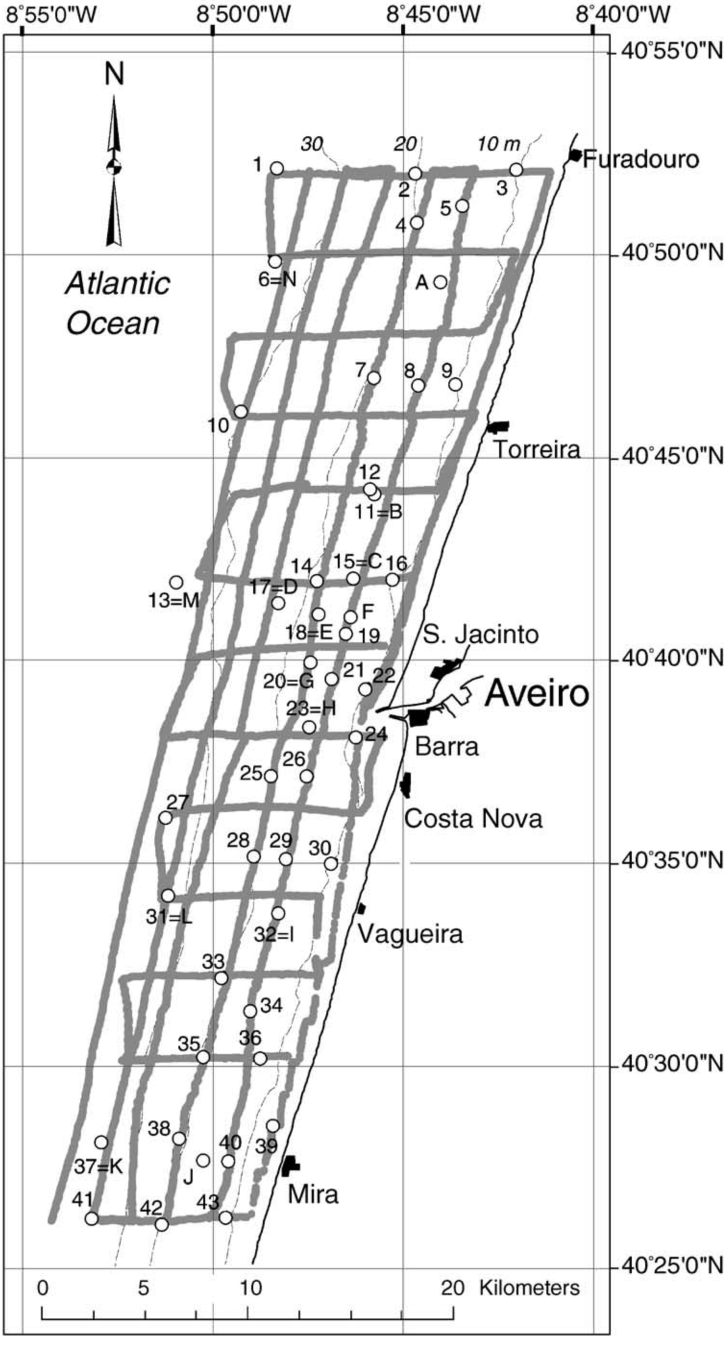

Fig. 1. Study area showing the acoustic survey lines, the sampling sites for the study of superficial sediments (numbered 1 to 43) and the sampling sites for the study of benthic communities (named A to N). Depth contour lines in meters (dashed lines).

manoeuvreable "Ciclone" was able to access the zone adjacent to the surf zone during limited periods of calm sea conditions.

2.2. Acoustic classification

On encountering the seafloor, the echo sounder pulse is reflected and scattered at the seabed–water interface, and by the material in the immediate sub-bottom. The returned pulse is acquired by the transducer, transferred to the data acquisition software (QTC VIEW), merged with the position data and transmitted to the computer for display and post-processing. QTC VIEW analyses the first seabed echo with a series of algorithms, for energy and shape characteristics in both frequency and time domains (Collins, 1996). The result is a digital description of the echo consisting of 166 variables (Collins and Lacroix, 1997). This data set is reduced using principal component analysis (PCA). Each echo is then represented by three values (Q_1, Q_2, Q_3) corresponding to the three first principal components (Collins and McConnaughey, 1998). This data matrix is then submitted to cluster analysis (K-means algorithm) to obtain acoustic classes, using the post-processing software QTC IMPACT™ v3.0 (Anonymous, 2002). The cluster procedure is based on a progressive splitting progress. Initially, a single class is displayed, corresponding to the full data cloud (Q-space). This cloud is then split into two. The process of splitting is continued as long as the overall statistical descriptors of the clusters improve (Anonymous, 2002). When points from a single acoustic class are plotted in Q-space they form a cluster, defined as an ellipsoid. Points from different acoustic classes will form different clusters.

Statistical descriptors are provided within QTC IMPACT to indicate the optimal split level. One of these is the total score, corresponding to the sum of the scores of the individual classes. Initially the total score decreases rapidly as a function of the splitting level. Further splits lead to smaller changes in the total score. When the number of splits is plotted against total score, the inflection point of the resulting curve gives an indication of the optimal splitting level (Anonymous, 2002). Another descriptor is the Cluster Performance Index rate (CPI rate). CPI rate is based on the Cluster Performance Index (CPI), which measures the ratio of the distance between cluster centres and the extent of the clusters in the Q-space. CPI generally increases as a function of the splitting level but the CPI rate, defined as $\mathrm{CPI}(n)=(\mathrm{CPI}(n)-\mathrm{CPI}(n-1))/\mathrm{CPI}(n-1)$, tends to be at a maximum at the optimal split level (Kirlin and Dizaji, 2000). Total score and CPI rate are the main aids in deciding the final classification to retain. However, as with any other classification procedure, further acoustic classes may be considered, as long as they are interpretable. Each acoustic record in the final classification file contains date, time, latitude and longitude, depth, Q_1, Q_2 and Q_3 values, class name, a confidence percentage and a probability percentage. The confidence value of a record is the probability that the record belongs to the class to which it has been assigned. It is a measure of the covariance-weighted distances between the position of the record in Q-space and the positions of all cluster centres (Anonymous, 2002). The probability value of a record is based on the position of that record in Q-space and the characteristics of the class to which it has been assigned. It is a measure of closeness to the cluster centre, weighed by the covariance of the cluster in the direction of the record (Anonymous, 2002).

2.3. Laboratory analyses

Sediment grain-size was analysed by wet and dry sieving (Quintino et al., 1989). The silt and clay fraction (fine particles, with diameter below 0.063 mm) and the gravel fraction (particles with diameter above 2.000 mm) were expressed as a percentage by dry weight of the total sediment. The sand fraction (0.063–2.000 mm) was dry sieved through a battery of sieves spaced at 1 phi (Φ) unit ($\Phi = -\log_2$ the particle diameter expressed in mm). The sediment was classified according to the median value (P_{50}), corresponding to the diameter that has half the grains (by weight) finer and half coarser (Trask, 1930), following the Wentworth scale (Doeglas, 1968). The median value was obtained graphically, by tracing each individual sediment cumulative frequency curve on probability paper. The final sediment classification adopted the description "silty" for those samples with a silt and clay fraction above 5% of the total sediment (dry weight). Also, following the nomenclature proposed by Willman (Pettijohn, 1975), coarse and very coarse sands were named pebbly sand and sandy gravel, if their gravel content was between 5% and 25% and between 25% and 50% of the total sediment, respectively (dry weight).

Macrofaunal samples were sieved through a 1-mm mesh screen, and the retained material fixed in 4% buffered formalin, stained with Rose Bengal. In the laboratory, individual samples were washed over a 500-μm sieve, and the animals sorted and identified to the lowest possible taxonomic level. For each sample, a species list and their relative abundances were determined.

2.4. Sedimentary and biological data analysis and acoustic class mapping

The sedimentary and the biological data were submitted to ordination analysis, performed respectively by nonmetric multidimensional scaling (MDS) with the software PRIMER v5 (Clarke and Gorley, 2001) and by correspondence analysis, with the software MVSP v3.12d (Kovach, 1999).

The sedimentary data consisted of a matrix of 43 sites × 7 variables (the granulometric classes). The normalized Euclidean distance was used to produce a distance matrix for submission to MDS. The final diagram, represented in two dimensions (horizontal and vertical axes), includes the respective stress value (Clarke and Warwick, 1994). This value is a measure of the distortion associated with the representation of the multidimensional distance matrix in two dimensions. If it is below 0.10, the representation is considered very good. If it is above 0.30, the final diagram should not be considered a reliable representation of the distance matrix (Clarke and Warwick, 1994).

The biological data consisted of a matrix of 14 sites × 173 variables, corresponding to the species abundances. Data were square-root-transformed and submitted to correspondence analysis.

For the acoustic data, the following data fields were extracted from the final data file written during QTC IMPACT processing (the "DAT" file): the three Q values, geographic position, acoustic class, class confidence and the class probability value. This data was imported into a GIS (Arc View 8.1) to produce acoustic diversity maps.

3. Results

The results of the acoustic classification up to the fourth split are shown in Table 2. The optimal solution was obtained at the second split, when the total score begins to stabilize and the CPI rate attains its maximum value. At this split level, three acoustic classes were identified and named A, B and C (cf. Table 2). Their geographical distribution is presented in Fig. 2. These classes exhibit a very clear inshore–offshore pattern, neither related to the bathymetry contours, nor parallel to the shoreline. The stability of the acoustic classification is supported by the agreement of the acoustic classification where survey lines intersect.

Fig. 2 also presents the MDS ordination diagram relative to the sediment grain-size data, on top of which the sediment classification is represented. The sample distribution on the MDS defines a gradual sediment succession, from the very coarse to the very fine sands. On top of the acoustic pattern, each sediment sample is also represented according to the sediment classification, showing the close relationship between some of the acoustic classes and the sediment types: class A includes all the coarser sands (medium, coarse and pebbly sand and sandy gravel); class B, the very fine sand; and class C, the fine sand. The survey area is thus characterised by a variety of sands, ranging from very fine to very coarse with more than 25% gravel content (Table 3), all with very low fines content. The highest values of fines were recorded at sites 25 and 39, with silt and clay fractions between 5% and 10% of the total sediment weight (cf. Table 3). No obvious bottom features were detected, such as emergent biogenic structures, algal mats or bedrock. The whole survey area may be described as a relatively monotonous sublittoral sandy plain with a gentle slope. At shallower depths, the sand tends to be finer, with the exception of a

Table 2
Acoustic classification statistics obtained up to the fourth split (five classes)

Split	Total score	CPI	Class	Members	Chi^2	Score	CPI rate
0	93 878 627.97	–	–	51 695	1816.01	93 878 628	–
1	6 590 391.00	10.30	A	27 344	103.51	2 830 287	–
			B	24 351	154.41	3 760 105	
2	3 873 367.48	26.78	A	26 810	85.88	2 302 529	1.60
			B	10 433	94.25	983 277	
			C	14 452	40.66	587 562	
3	3 341 488.47	58.14	A	26 783	84.19	2 254 800	1.17
			B	9700	81.79	793 404	
			C	8568	11.67	100 019	
			D	6644	29.09	193 266	
4	3 020 399.58	115.73	A	13 449	70.78	951 971	0.99
			B	9628	86.51	832 936	
			C	8560	10.89	93 193	
			D	6608	26.55	175 431	
			E	13 450	71.89	966 869	

The optimal solution is obtained at the second split, corresponding to three acoustic classes. Total score = sum of the scores of the individual classes; CPI = cluster performance index; Members = number of data points in each class; Chi^2 = measure of the clumpiness of each cluster in the Q-space; Score = a product of the number of members and the Chi^2 value; CPI rate = $[CPI(n)-CPI(n-1)]/CPI(n-1)$, where n is the split number.

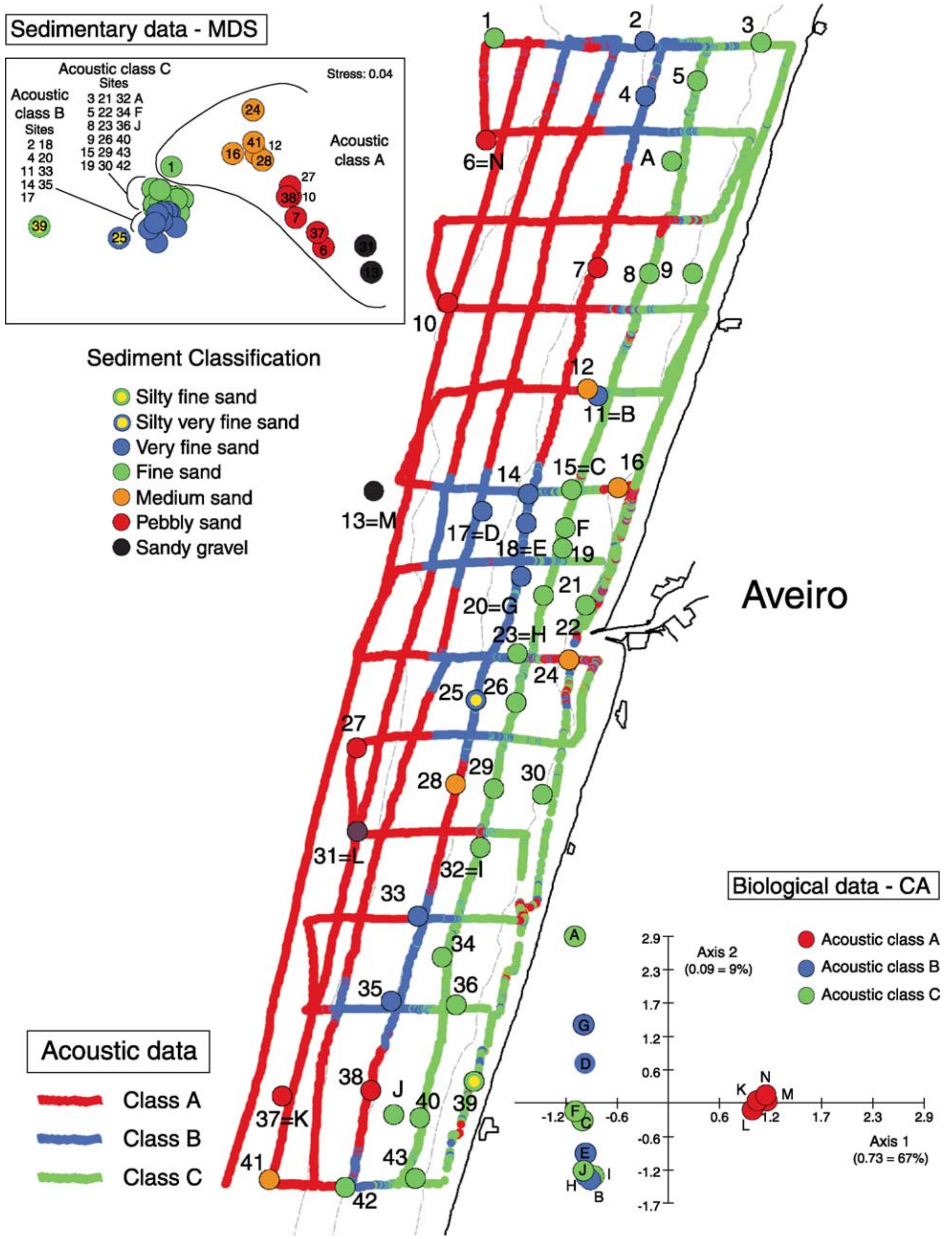

Fig. 2. Spatial distribution of the acoustic classes A, B and C, obtained at the optimal split level. Each sampling site is represented on top of the acoustic survey lines, showing the respective sediment classification. The same representation is shown on top of the upper left 2-D nonmetric multidimensional scaling (MDS) of the samples grain-size data. The lower right ordination diagram represents the distribution of the samples on planes 1 – 2 of a correspondence analysis (CA) of the biological data. In this diagram, the samples are coloured in agreement with their position within the three acoustic classes.

Table 3
Superficial sediment grain-size analysis, expressed as percent of total sediment dry weight, median value in phi units (Φ) and sediment classification

Site	>2.0 (mm)	1.0–2.0 (mm)	0.5–1.0 (mm)	0.250–0.500 (mm)	0.125–0.250 (mm)	0.063–0.125 (mm)	< 0.063 (mm)	Median (Φ)	Sediment classification
1	0.10	0.26	2.17	14.01	69.41	13.09	0.95	2.50	Fine sand
2	0.01	0.09	0.83	6.24	42.02	49.26	1.55	3.02	Very fine sand
3	0.06	0.10	0.47	1.99	48.41	47.82	1.15	2.99	Fine sand
4	0.13	0.05	0.60	3.81	45.14	48.76	1.51	3.01	Very fine sand
5	0.51	0.59	3.27	11.38	49.64	33.46	1.15	2.73	Fine sand
6	7.98	29.66	46.76	14.24	0.93	0.05	0.37	0.29	Pebbly sand
7	9.94	20.54	35.66	31.65	1.64	0.13	0.44	0.55	Pebbly sand
8	0.18	0.09	2.40	17.64	42.78	35.74	1.17	2.71	Fine sand
9	0.02	0.18	3.03	9.88	51.54	33.50	1.85	2.78	Fine sand
10	5.38	13.88	45.76	32.90	1.76	0.04	0.28	0.70	Pebbly sand
11	0.09	0.13	2.16	9.95	27.56	58.47	1.63	3.12	Very fine sand
12	1.41	0.69	26.75	58.24	7.94	4.75	0.22	1.37	Medium sand
13	26.99	29.94	34.14	8.13	0.47	0.03	0.31	−0.21	Sandy gravel
14	0.00	0.03	0.37	0.73	47.40	49.72	1.74	3.02	Very fine sand
15	0.16	0.12	1.57	6.20	42.07	48.41	1.48	2.99	Fine sand
16	0.35	0.84	10.57	60.04	19.26	8.41	0.53	1.70	Medium sand
17	0.01	0.07	0.82	1.83	24.65	69.90	2.72	3.25	Very fine sand
18	0.00	0.03	0.23	0.81	39.97	56.99	1.97	3.10	Very fine sand
19	1.47	1.17	0.85	4.12	44.07	46.73	1.58	2.98	Fine sand
20	0.04	0.02	0.06	0.64	36.32	59.61	3.30	3.19	Very fine sand
21	0.04	0.06	0.21	1.46	59.46	36.73	2.04	2.90	Fine sand
22	0.28	0.17	1.17	4.39	50.65	40.76	2.58	2.90	Fine sand
23	0.08	0.09	0.84	6.01	53.70	36.58	2.70	2.81	Fine sand
24	0.01	0.14	9.26	84.10	5.90	0.14	0.45	1.48	Medium sand
25	0.03	0.04	0.08	0.61	30.59	63.33	5.34	3.25	Silty very fine sand
26	0.03	0.08	0.42	2.29	60.13	35.08	1.98	2.85	Fine sand
27	2.38	11.47	51.09	31.85	2.91	0.03	0.27	0.75	Coarse sand
28	0.53	2.87	33.81	53.45	8.14	0.67	0.52	1.20	Medium sand
29	0.02	0.03	1.03	8.87	47.65	40.10	2.29	2.88	Fine sand
30	0.08	0.11	0.74	5.63	47.37	43.04	3.03	2.95	Fine sand
31	29.19	22.21	25.25	21.83	1.31	0.03	0.18	−0.05	Sandy gravel
32	0.19	0.11	1.17	13.04	35.52	48.42	1.55	2.99	Fine sand
33	0.03	0.01	0.13	0.97	45.37	51.06	2.43	3.05	Very Fine sand
34	0.06	0.04	0.16	0.51	49.60	47.48	2.16	3.00	Fine sand
35	0.17	0.04	0.18	0.72	39.21	56.92	2.77	3.11	Very Fine sand
36	0.11	0.07	0.13	0.95	55.51	40.80	2.44	2.95	Fine sand
37	18.79	21.42	33.33	23.54	2.63	0.04	0.25	0.29	Pebbly sand
38	5.75	12.78	44.25	34.81	1.80	0.14	0.48	0.74	Pebbly sand
39	0.20	0.07	0.17	1.94	54.47	33.74	9.41	2.94	Silty Fine sand
40	0.10	0.07	0.48	3.82	48.22	45.34	1.97	2.99	Fine sand
41	0.07	0.58	23.52	65.34	9.80	0.12	0.57	1.35	Medium sand
42	0.11	0.11	1.28	17.62	43.73	34.98	2.17	2.73	Fine sand
43	0.06	0.21	0.53	2.06	65.37	29.44	2.33	2.80	Fine sand
A	0.02	0.07	1.17	4.53	52.83	39.28	2.16	2.86	Fine sand
F	0.05	0.16	0.22	0.81	54.14	42.18	2.61	2.95	Fine sand
J	0.04	0.05	0.36	3.01	62.14	32.95	1.53	2.80	Fine sand

few sites closer to the shore or at the entrance channel of "Ria de Aveiro", where medium sand occurred (sites 16 and 24, cf. Fig. 2 and Table 3). Coarser sediments (pebbly sand and sandy gravel) occurred offshore, generally beyond 20 m depth. Apparently, the separation between the finer and the coarser sediments is quite sharp, as few sites with medium sand were detected offshore (sites 12, 28 and 41, cf. Table 3 and Fig. 2). The relationship between the three acoustic classes and the sediments types was consistent, irrespective of water depth, with the few shallower areas where the acoustic class A was identified, (entrance of "Ria de Aveiro") also being classified as medium sand (cf. Fig. 2 and Table 3, sites 16 and 24). There was a single exception, with site 1, classified as fine sand, being

Table 4
Comparison of the two biological assemblages, as defined by correspondence analysis

	Gravely sand community (offshore)		Fine/very fine sand community (inshore)	
Sampling sites	K, L, M, N		A, B, C, D, E, F, G, H, I, J	
Acoustic classes (cf. Fig. 2)	Class A		Classes B and C	
Total number of species sampled	173			
Total species richness (*S*)	136		72	
Mean species richness (S/0.1 m^2)	45.1		20.9	
Species present in more than 50% of the sites	45		32	
Species exclusive to each community	101		37	
Species common to both communities	35 (= 173 − (101 + 37))			
Total abundance (*A*)	11318		4191	
Mean abundance (A/0.1 m^2)	943.2		139.7	
Abundance of the species common to both communities	7537 (49% of the total)			
Abundance of the species exclusive to each community	6951 (61%)		1021 (24%)	
Dominant species, representing more than 1% of each community mean abundance (A/0.1 m^2). Species shown in bold are common to both lists.	Nematodes	232.2	***Mediomastus fragilis***	51.0
	Polygordius appendiculatus	205.4	*Magelona johnstoni*	32.2
			Donax cf. semistriatus	6.4
	Pisione remota	94.3	*Owenia fusiformis*	5.7
	Aonides oxycephala	73.4	***Spisula subtruncata***	4.2
	Protodorvillea kefersteini	57.9	*Pharus legumen*	4.1
	Gastrossacus spinifer	46.9	*Glycera tridactyla*	3.4
	Mediomastus fragilis	44.1	*Spiophanes bombix*	2.8
	Hesionura elongata	24.6	*Orchomenella nana*	2.3
	Glycera lapidum	14.9	*Ampelisca brevicornis*	2.2
	Copepodes	14.5	*Spio decoratus*	2.0
	Spisula subtruncata	13.8	*Ampelisca* sp.	1.7
	Paradoneis lyra	10.6	*Nephtys assimilis*	1.7
	Thracia papyracea	9.3	*Phaxas pellucidus*	1.6
			Bathyporeia guilliamsoniana	1.6
			Magelona filiformis	1.6

consigned to class A (Fig. 2). Apart from such consistency, there were however several sediment grain-sizes not differentiated by the acoustic data splits, namely the coarser sands within acoustic class A.

Fig. 2 also presents the correspondence analysis ordination results for the biological data. The sampling sites located within acoustic class A (K, L, M and N), are all plot close to each other on the positive pole of the correspondence analysis axis 1, while the remaining sampling sites (A to J) all fell on the negative side of the same axis (cf. Fig. 2). They belong to the acoustic classes B and C, and so a mismatch between the optimal acoustic classes splits (3 classes) and the biological community data is noticed (2 assemblages). The ordination of the biological data suggests two very contrasting benthic assemblages for the shelf area under study, as no continuity exists between the sites located on the positive and the negative pole of axis 1. These two benthic assemblages in fact only have a few shared species, namely dominant ones, and their primary biological variables, such as species richness and abundance, present very different values (cf. Tables 4 and 5). Although the benthic data does not support the acoustic split into three acoustic classes, it

Table 5
Benthic macrofauna succession from the offshore gravely sand community to the inshore fine/very fine sand community

	Gravely sand	Fine/very fine sand
Nematodes	232.2	
Polygordius appendiculatus	205.4	
Pisione remota	94.3	
Aonides oxycephala	73.4	
Protodorvillea kefersteini	57.9	
Hesionura elongata	24.6	
Gastrossacus spinifer	46.9	0.5
Copepods	14.5	1.0
Spisula subtruncata	13.8	4.2
Spio decoratus	3.5	2.0
Mediomastus fragilis	44.1	51.0
Euspira nitida	0.6	0.8
Anomura	0.2	0.4
Magelona johnstoni	0.3	32.2
Urothoe pulchella	0.1	0.6
Nassarius reticulatus	0.1	0.9
Phaxas pellucidus	0.1	1.6
Bathyporeia guilliamsoniana	0.1	1.6
Nephtys assimilis	0.1	1.7
Orchomenella nana	0.1	2.3
Magelona filiformis		1.6
Ampelisca sp.		1.7
Ampelisca brevicornis		2.2
Spiophanes bombix		2.8
Glycera tridactyla		3.4
Pharus legumen		4.1
Owenia fusiformis		5.7
Donax cf. semistriatus		6.4

The table was constructed using species contributing at least 3% of the total site abundance. Shaded values indicate the higher abundance value for each species.

is noticed that from the first to the second acoustic split, the acoustic class A remains almost unchanged, whereas the acoustic classes B and C were mainly produced from the subdivision of the previous class B, obtained at the first split (cf. Table 2, members). Splitting the acoustic data into two classes (first split, cf. Table 2) coincides with the major benthic assemblages in the shelf area under study, and renders it ecologically the most meaningful and interpretable.

4. Discussion

According to Collins and Lacroix (1997), the QTC VIEW seabed classification system is primarily influenced by bottom roughness and the density difference between the sediment surface and the overlying water. Collins and Galloway (1998), working in an area of the inner harbour of Vancouver, Canada, showed that the acoustic diversity measured by the QTC VIEW system successfully captured a high variety of seabed types, based on sediment grain size and the presence/absence of shell debris. Hamilton et al. (1999) in the Cairns area, Great Barrier Reef, Australia, also verified the agreement between the acoustic pattern and a variety of sediments, according to their grain size and texture properties. Preston et al. (1999) found that four geotechnical variables gave the highest correlation with acoustic classes: surface grain-size, porosity, shear strength and bearing strength. Studies conducted by Bornhold et al. (1999) in Southern Gulf Island of British Columbia, Canada, also showed that the QTC VIEW acoustic technique could reflect the seafloor sediment texture and other properties such as microtopography. Microtopography and ripple marks have been shown to influence the acoustic echo (Collins et al., 1996), and recent studies indicate that some infaunal species can affect single-beam acoustic backscatter (Self et al., 2001). All these studies indicate that superficial sediment grain-size is amongst the most important soft bottom properties that, directly or indirectly, influence acoustic backscatter. This has normally been shown when the survey area contains a variety of bottom types, including a range of fines content. Further examples include the study by Smith et al. (2001), for the characterisation of oyster bottom in Chesapeake Bay, USA, in which the authors were able to differentiate several grain-size bottom types and areas containing different proportions of sand, mud and shells, and the work by Ellingsen et al. (2002), in the Frænfjorden, western Norway, in which acoustic variety was generally in accordance with sediment grain-size.

However, none of the previous studies applied acoustic seabed classification to monotonic, clean sand dominated soft bottom habitats, as found in this study, with a lack of seafloor bottom diversity apart from the superficial grain size. Under these conditions, the acoustic approach clearly identified the two major benthic biotopes in the area, corresponding to two very contrasting communities; a fine to very fine sand community, located inshore, and a gravely sand community, located offshore. Compared to more spatially discrete grab based sediment sampling, the acoustic survey approach produces reliable habitat maps over large spatial scales, with considerably less sampling and laboratory effort (although ground-truth is still required).

The final acoustic map, incorporating three acoustic classes, closely followed the same inshore–offshore pattern as the environmental and the biological data. Whereas there was agreement between the distribution of the two major acoustic classes and the benthic communities, the third acoustic class, which refines the inshore–offshore gradient through the separation of the fine and very fine sands, showed no immediate relationship to the benthic communities' distribution. However, this separation may be of biological interest, as benthic samples taken in September 2000 (as part of a separate program), coinciding with the recruitment of the bivalve *Donax cf. semistriatus*, indicated that the density of recruits is much higher in the fine sands compared to very fine sands. Although the lower recruitment observed in the very fine sand could be depth-related, the two sediments present different compactness, which could also represent an important difference for the species. We believe that sediment compactness could be the reason behind the acoustic distinction shown in this work between the fine and the very fine sands, as measured by the shallower penetration of the grab sampler in the very fine sand compared to penetration in the coarser sediments. This could also account for the fact that no acoustic difference was apparently noticed between medium sand, pebbly sand and sandy gravel. Sediment compactness seemed comparable among these sediments, with the grab sampler always showing maximum penetration in all these sediments. This same sediment characteristic could explain the misclassification of the sediment taken in site 1, the only fine sand site with the same acoustic classification as coarser sands. When compared to the other sediment samples classified as fine sand, the sediment sample from site 1 was higher in the fractions with grain-size between 0.250–0.500 and 0.125–0.250 mm (cf. Table 3). Such a difference could explain the fact that the sediment sampler penetration was also higher in this fine sand than in any of the other sediments with similar median classification.

5. Conclusions

The optimal acoustic classification identified an inshore–offshore gradient, which corresponds to the separation of fine, very fine and coarser sands. The acoustic classification was apparently unable to distinguish between the several grades of coarser sediments. Observations during ground-truth sampling suggest that similar sediment compactness could be the main reason behind this result. Although very fine and fine sediments have indistinguishable benthic communities, one of the dominant species, the bivalve *Donax cf. semistriatus*, recruits only to the finer sands, thus suggesting the acoustic sediment assessment as a rapid and efficient means to identify suitable biotopes for this economically exploited species. However, the acoustic seabed classification clearly delineated the two major benthic biotopes present in this shelf area, corresponding to an inshore fine/very fine sand community and an offshore gravely sand community.

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Sea-bottom classification across a shallow-water bar channel and near-shore shelf, using single-beam acoustics

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Abstract

An acoustic ground discrimination system (QTC VIEW, Series IV) was used to identify and map the bottom acoustic diversity in the bar channel of Ria de Aveiro, Western Portugal. The majority of the survey area presented shallow depth for this type of equipment, ranging mainly from 5 to 15 m. Depth occasionally reached 25 m in specific areas located across the entrance channel, dug by the strong tidal currents, reaching 3 m/s. The acoustic data were submitted to manual and auto-cluster and the results obtained from both procedures were coherent. Using aids to the acoustic classification and ground-truth sediment data, a final solution consisting of four acoustic classes was reached. Their geographical distribution was coincident with the spatial distribution of the major bottom types and sediment groups (hard bottom, coarse sand, medium sand and fine sand), identified through multivariate analysis of the grain-size data, and reflected the complex hydrodynamics of the entrance channel. The acoustic pattern was coincident at the intersections of the acoustic survey lines, assuring the repeatability of the acoustic procedure. Overall, the acoustic approach showed consistent results for the assessment and mapping of the benthic habitats in this shallow-water coastal area, providing a very valuable tool in an area where conventional sediment sampling is less favourable, namely due to strong tidal currents and frequent ship traffic, such as the entrance channel of Ria de Aveiro and the near-shore adjacent shelf.

Keywords: acoustic ground discrimination system (QTC VIEW); benthic biotopes; manual cluster; auto-cluster; shallow water; Portugal

1. Introduction

Assessing and mapping the diversity of seabed habitats has recently experienced a growing use of acoustic ground discrimination systems (AGDS), operating with single-beam echo sounders (Greenstreet et al., 1997; Hamilton et al., 1999; Kloser et al., 2001; Anderson et al., 2002; Ellingsen et al., 2002; Freitas et al., 2003a,b). A number of features have contributed to the good reputation earned by this acoustic approach, namely its non-intrusive properties, the ability to cover large areas with almost continuous sampling rates, the discrimination of a variety of soft sediment types and bottom features, their lower cost compared to side-scan sonar or multi-beam systems. Some systems register and display the full echo waveform envelope upon which the classification procedure operates. This is the case for the QTC VIEW™ acoustic system used in the present work and represents a major difference between this system and the majority side-scan sonar or multi-beam based acoustic systems (Kenny et al., 2003). Nevertheless, the lack of a full theoretical background relating the echo properties to the bottom features requires that a reliable empirical use of the equipment is established in order to

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obtain consistent and comparable results from survey to survey.

Previous studies performed with the single-beam acoustic seabed classification system QTC VIEW (Series IV) revealed its ability to identify and map seabed types, characterized by distinct acoustic signatures. Several studies undertaken with this system showed that the acoustic response depends namely on the seabed roughness, sediment grain size, the presence/absence of shell debris and some infaunal species, texture properties of the sediment and sediment porosity (Collins and Lacroix, 1997; Collins and Galloway, 1998; Hamilton et al., 1999; Preston et al., 1999; Preston, 2001; Self et al., 2001; Anderson et al., 2002; Ellingsen et al., 2002; Freitas et al., 2003a,b). QTC VIEW Series IV has been seldom employed in shallow waters, being recognized that the system is not designed to survey in less than 5 m depth (Preston, personal communication).

Having in mind the application of this AGDS for the characterisation of seabed habitats, this study aimed to analyse the efficiency of the acoustic system QTC VIEW Series IV to work in shallow waters, and in particular in areas where conventional sediment sampling is less favourable due to strong tidal currents and frequent ship traffic. In such areas, namely the near shelf and entrance channels of shallow-water systems in exposed coastal areas, conventional sediment sampling must be optimised as much as possible. Such coastal systems are a common feature of exposed sandy shorelines, as it is the case of the Portuguese coast. Under these circumstances, acoustic systems, if successful, may be the best option to characterize and monitor the spatial and temporal evolution of coastal bottom habitats.

2. Material and methods

2.1. Acoustic and ground-truth sediment sampling

The study area covered approximately 16 km^2 and corresponds the narrow entrance channel of Ria de Aveiro and the adjacent near-shore shelf. Depth ranged mainly from 5 to 15 m, occasionally reaching 25 m only in very specific areas located across the entrance channel, dug by the strong tidal currents, of over 3 m/s (Dias et al., 2000, 2003). In the near shelf, regular survey lines were positioned delineating a grid, whereas in the narrow entrance channel, the survey comprised transects positioned along the navigation channel (Fig. 1). The acoustic survey was conducted with a QTC VIEW Series IV connected to a 50-kHz echo sounder, with the transducer mounted on the side of the research vessel "N.R.P. Andrómeda". A laptop was used for data acquisition, display and storage, and a Global Position System (DGPS) to acquire the coordinates of the echoes. The echo sounder and QTC VIEW settings are presented in Table 1. Ground-truth samples for sediment grain-size analysis were obtained using a 0.1 m^2 Smith-McIntyre grab. Samples were collected at 19 sites, the positioning of which was delineated as soon as a preliminary classification of the acoustic data was obtained, in order to optimise sampling effort (cf. Fig. 1).

2.2. Data analysis

The acoustic data acquired by the QTC VIEW, were submitted to Principal Component Analysis (PCA). This procedure reduces the digital echo description to three values ($Q1$, $Q2$, $Q3$) corresponding to the coordinates on the first three PCA axes (Collins and McConnaughey, 1998). Using the post-processing software QTC IMPACT™ v3.40, this data matrix was submitted to a manual cluster analysis (K-means) that is based on a progressive splitting process. Initially one acoustic class is displayed, corresponding to the full data cloud in Q-space (the data space formed by $Q1$, $Q2$, $Q3$). This cloud is then subdivided into two clusters, corresponding to two different acoustic classes. The spatial distribution of the cluster in the Q-space indicates how acoustically similar are the seabeds they represent. Points from three acoustically distinct seabeds are expected to form three distinct clusters, corresponding to three different acoustic classes. At each split a series of statistical descriptors are provided for each class and used to decide how further to divide the data set. One of these descriptors is Total Score (the sum of all scores of the individual classes). As splitting proceeds, Total Score decreases and the inflection point is taken as a strong indication of the best split level (QTC IMPACT User Manual, 2004). A complementary indication is given by the Cluster Performance Index rate (CPI rate $=$ CPI $(n) -$ CPI $(n-1)/$CPI $(n-1)$). This descriptor measures the ratio of the distance between the cluster centres and the extent of the clusters in Q-space, and tends to be maximum at the optimal split level (Kirlin and Dizaji, 2000). Although important for the final classification result, these two descriptors should be taken as indicators, as it is acknowledged that the Total Score inflection point not always coincides with the maximum CPI rate. Also as with any other classification procedure, the final number of classes also considered how interpretable they were through ground-truth data.

The acoustic data were also analysed using an auto-cluster procedure (QTC IMPACT User Manual, 2004), with the objective to compare the results obtained with the two classification procedures. The auto-cluster procedure in QTC IMPACT v3.40 uses a simulated annealing K-means algorithm in order to find an optimal number of classes. The optimal number of classes is indicated on a graphical display and is reached when the Total Score is at minimum (QTC IMPACT User Manual, 2004).

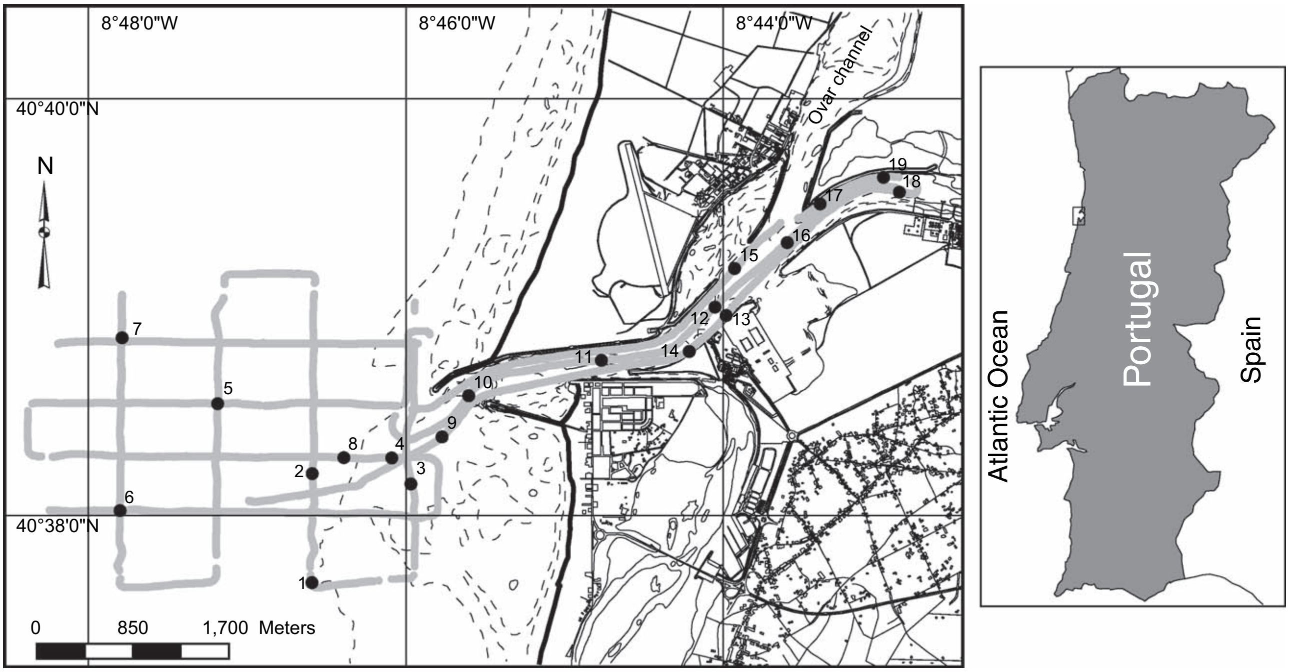

Fig. 1. Study area: Ria de Aveiro bar channel and near-shore shelf, showing the acoustic survey lines from QTC VIEW (Series IV) and the 19 sampling sites for the sediment grain-size analysis.

The final acoustic cluster file was imported into a Geographical Information System (Arc View v8.1, Minami, 2000) in order to produce maps of acoustic diversity, for which latitude, longitude and class name per each echo data point were extracted from the QTC IMPACT output file.

The data concerning the sediment samples were analysed by wet and dry sieving (Quintino et al., 1989). The silt and clay fraction (fine particles, with diameter below 0.063 mm) was expressed as a percentage of the total sediment (dry weight). The sand fraction (particles with diameter between 0.063 and 2.000 mm) and the gravel fraction (particles with diameter above 2.000 mm) were sieved through a battery of sieves spaced at 1 ϕ size intervals ($\phi = -\log_2$ the particle diameter expressed in mm). For each sediment, the median value (P_{50}) was calculated. The grain-size data matrix, including for each site the amount of sediment in each grain-size class expressed as a percentage of the whole sediment (dry weight), the median value in phi units, and the sampling depth in meters, was analysed with multivariate classification and ordination analysis, using the software PRIMER v5 (Clarke and Gorley, 2001). The sediment from each site was also classified following Table 2, according to the Wentworth scale based on the median value (P_{50}) and the percent content of fine particles (Doeglas, 1968; Larsonneur, 1977).

Table 1
Survey base settings for the echo sounder (Suzuki ES-1025) and the QTC VIEW (Series IV)

	Parameter	Setting
Echo sounder	Pulse duration	300 μs
	Beam width	19°
	Transmit power	100 Watt
	Range	0–60 m
	Ping rate	5 per second
QTC VIEW	Base gain	10 dB
	Depth	Maximum: 40 m Minimum: 5 m Reference: 10 m

3. Results

The results obtained with the manual cluster analysis are shown in Table 3. According to the CPI rate, the optimal classification corresponds to the second split (three acoustic classes), where the CPI rate is maximum. As for the Total Score Fig. 2A shows how it diminishes as splitting occurs. Total Score diminishes abruptly up to the second split (three acoustic classes) and tends to level at the third split (four acoustic classes), after which the diminishing of Total Score values shown in Table 3 become imperceptible in the graph of Fig. 2A. Optimal classification may thus consider three or four acoustic classes, corresponding to the second and the third split level, respectively. Fig. 2B shows how Total Score diminishes with increasing number of acoustic classes in the auto-cluster procedure. The simulated annealing K-means procedure in auto-cluster results in a different Total Score each time the annealing procedures runs

Table 2
Sediment classification adapted from Wentworth (Doeglas, 1968) and Larsonneur (1977)

Median (ϕ)	Sediment classification		Fines content (%) <5	5–25	25–50
(−1)–0	Sand	Very coarse	Clean	Silty	Very silty
0–1		Coarse			
1–2		Medium			
2–3		Fine			
3–4		Very fine			
>4	Mud			Above 50%	

(QTC IMPACT User Manual, 2004). Up to four acoustic classes, this variability is imperceptible but becomes obvious from five acoustic classes onwards, as shown in Fig. 2B, in which the line is draw through the minimum and the maximum score value for each number of acoustic classes. Although the absolute minimum score value was obtained with six classes (cf. Fig. 2B), the procedure shows high variability within each class number as Total Score starts to level out, i.e. after four acoustic classes. Up to four acoustic classes the score iterations within each class were very similar, indicating that the possible alternative results were very close to each other. Beyond five acoustic classes, inclusive, the score iteration values have large amplitude changes, indicating a high uncertainty to obtain a minimum score for those classes. Although the absolute minimum was obtained with six classes, these results suggest an optimal classification with four acoustic classes. The geographic distribution of three and four acoustic classes obtained with manual cluster and four and five acoustic classes obtained with auto-cluster, are shown in Fig. 3. The quality of the acoustic classification is demonstrated by the agreement between the intercepting survey lines. The spatial pattern obtained with three and four classes is very clear, whereas the fifth class in the auto-cluster introduces noise and a lesser clear final pattern. This is in agreement with the less clear score results of five acoustic classes in auto-cluster (cf. Fig. 2B).

Concerning the sedimentary data, Table 4 shows the results of the sediment grain-size analysis for each site, also including the sampling depth, the median value and the sediment classification. Besides the hard bottom areas, detected close to the artificial margins of the navigation channel (sites 13, 14 and 17), the soft sediments showed three major sediment groups in the study area, as shown in the classification and ordination diagrams presented in Fig. 4 (top). The three sediment groups correspond mainly to coarse, medium and fine sand, according to the sediment classification criteria considered (cf. Table 4), but also included one site with sandy gravel (site 12) and another with very fine sand, although in this case the median value is just slightly above 3.00 ϕ (site 7, Table 4). All soft sediments presented very low silt and clay content (<5%), as would be expected in an area where tidal currents daily exceed 1 m/s and often reach 3 m/s (Dias et al., 2000; personal communication). In Fig. 4 (bottom), the three main soft sediment types and the hard bottom are represented on top of the acoustic diversity map, considering four acoustic classes as the final result. The relationship between the acoustic and the sedimentary data shows the following correspondences: acoustic class A, located close to the margins of the navigation channel, corresponds to a rocky bottom,

Table 3
Manual clustering – acoustic classification statistics, obtained up to the seventh split (eight classes), for the entrance of Ria de Aveiro. Total Score = sum of the scores of the individual classes; CPI = Cluster Performance Index; CPI rate = [CPI (n) − CPI (n − 1)]/CPI (n − 1), where n is the split number

Split	Number of classes	Total Score	CPI	CPI rate
0	1	358 771.97	–	–
1	2	122 082.28	1.97	–
2	3	20 486.18	10.23	4.19
3	4	13 782.09	17.25	0.69
4	5	11 793.06	31.55	0.83
5	6	11 988.08	56.37	0.79
6	7	10 504.74	80.69	0.43
7	8	9849.21	124.62	0.54

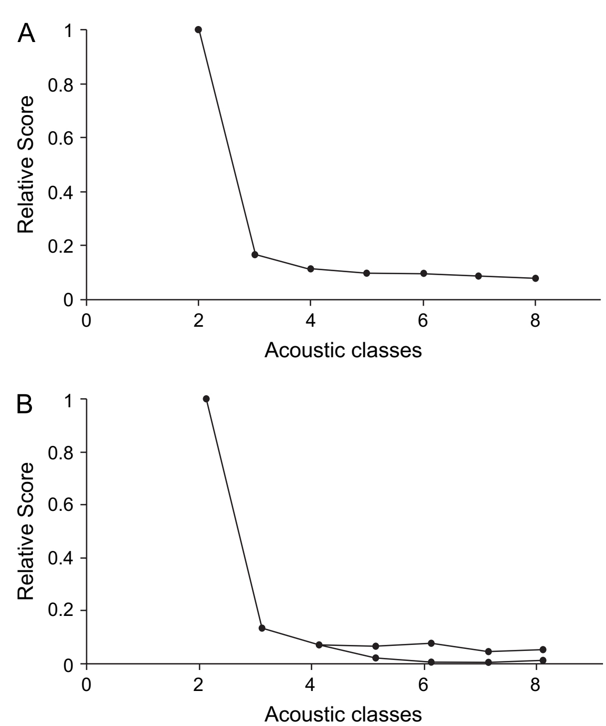

Fig. 2. Relative score, expressed as standardized values for the Total Score obtained with two acoustic classes. A – manual clustering; B – auto-cluster, showing the maximum and the minimum iteration score values, only perceptible as Total Score tends to level.

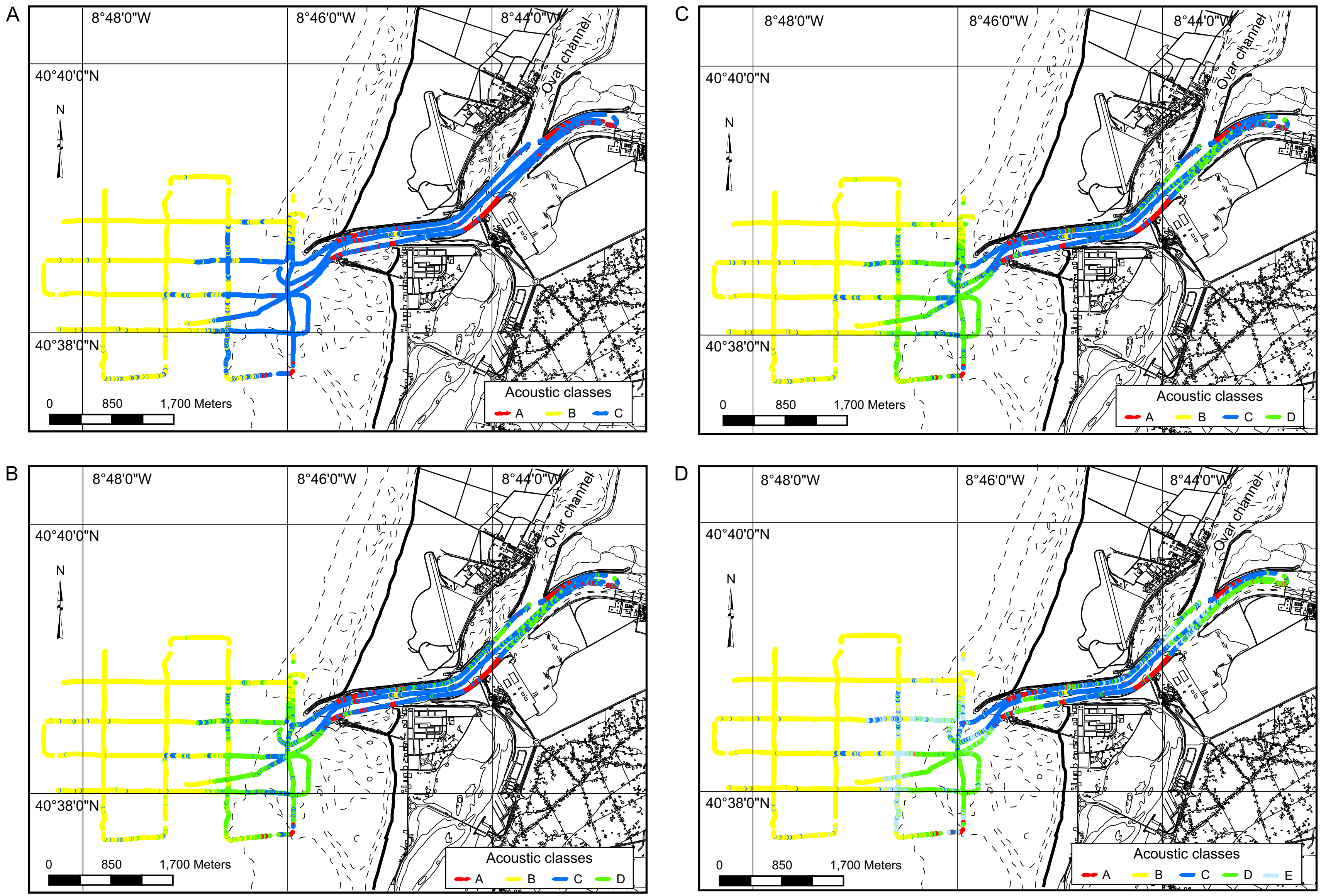

Fig. 3. GIS representation of the acoustic diversity at the bar channel of Ria de Aveiro and the near-shore shelf. A – three acoustic classes obtained with manual cluster. B – four acoustic classes obtained with manual cluster. C – four acoustic classes obtained with auto-cluster. D – five acoustic classes obtained with auto-cluster.

Table 4
Superficial sediment grain-size analysis from the bar channel of Ria de Aveiro and near-shore shelf. Grain-size classes (in mm) values are expressed as percent of total sediment dry weight and the median value in phi units (ϕ). Sediment classification according to Table 2, except for site 12 (sandy gravel) and sites 13, 14 and 17 (hard bottom)

Site	Depth (m)	>4.0 (%)	2.0–4.0 (%)	1.0–2.0 (%)	0.5–1.0 (%)	0.250–0.500 (%)	0.125–0.250 (%)	0.063–0.125 (%)	<0.063 (%)	Median (ϕ)	Sediment classification
1	9	0.04	0.05	0.19	1.57	10.06	84.57	3.52	0.02	2.45	Fine sand
2	10	0.00	0.03	0.20	2.99	56.73	39.14	0.78	0.12	1.82	Medium sand
3	7	0.59	2.02	6.98	15.80	66.58	7.62	0.22	0.18	1.37	Medium sand
4	8	11.09	13.27	24.33	29.43	19.01	2.67	0.19	0.01	0.04	Coarse sand
5	12	0.01	0.00	0.09	0.38	3.46	57.37	37.12	1.56	2.80	Fine sand
6	15	0.03	0.04	0.07	0.42	3.79	51.56	41.92	2.17	2.89	Fine sand
7	15	0.01	0.07	0.11	0.77	13.34	35.01	48.51	2.17	3.01	Very fine sand
8	7	0.00	0.02	0.07	1.95	86.82	10.78	0.23	0.14	1.55	Medium sand
9	9	0.00	0.00	0.14	2.18	82.60	14.78	0.24	0.06	1.58	Medium sand
10	26	27.59	10.36	5.57	16.29	37.21	2.74	0.20	0.05	0.40	Coarse sand
11	23	16.76	14.26	13.93	18.68	33.77	2.41	0.13	0.06	0.27	Coarse sand
12	16	40.15	12.43	10.18	10.41	25.44	1.15	0.07	0.18	−1.21	Sandy gravel
15	10	2.91	0.78	1.02	20.26	68.77	6.06	0.17	0.03	1.36	Medium sand
16	12	0.00	0.00	0.14	1.74	87.31	10.64	0.15	0.02	1.55	Medium sand
18	6	6.45	8.86	10.17	20.10	46.13	7.65	0.30	0.36	1.10	Medium sand
19	12	23.80	15.06	7.31	6.19	24.84	16.55	2.70	3.54	0.62	Coarse sand

related with the artificial margins. The acoustic class B, located on the coastal shelf, corresponds to clean fine sand. Acoustic class C is the predominant class in the navigation channel and corresponds to the higher energy area occupied by coarse sand. The coarse sands in the navigation channel are only interrupted at the interception between this channel and the Northern Ovar channel. Finally, the acoustic class D corresponds to clean medium sand. This acoustic class is mainly located near the mouth of the entrance channel and makes the transition from the coarse sand from the navigation channel to the fine sand of the near-shore shelf. The acoustic solution with only three acoustic classes would have completely omitted the differentiation between medium and coarse sand (cf. Figs. 3A, B and 4), whereas the solution with five acoustic classes suggests a detailed separation within the medium sands resulting in a less clear spatial pattern, unexplainable by the currently available ground-truth data (cf. Figs. 3C, D and 4).

4. Discussion

According to Collins and Lacroix (1997), the roughness of the seabed and the density difference between the water and the seabed material have important influences on the QTC VIEW seabed classification system. Later, Collins and Galloway (1998) showed that the acoustic diversity could also depend on the sediment grain size and the presence/absence of shell debris. Hamilton et al. (1999) noted that the texture properties of the sediment, not only grain size, also influence the acoustic diversity. Studying the relationships between several substrate characteristics and QTC VIEW acoustic classes, Preston et al. (1999) also suggested that porosity and grain size were the best descriptors of the superficial bottom properties. Recently, Freitas et al. (2003a) showed the ability of the QTC VIEW system to discriminate different sediment types in a relatively monotonous soft bottom area with almost no silt and clay content, and also in areas where the sediment gradually changes from fine sand to mud with the silt and clay content ranging, respectively, from below 5% to above 80% of total sediment (Freitas et al., 2003b).

These works indicate that the acoustic classification is particularly responding to the sediment type, namely grain-size. However, none of the above mentioned studies were conducted in shallow areas, as was the case of the present study. The results obtained confirm the sensitivity of the acoustic system (QTC VIEW, Series IV) to the sediment grain-size characteristics and demonstrate its efficiency to assess and map seabed habitats on relatively shallow areas. The distribution of the superficial sediments in the entrance channel and the adjacent near-shore shelf well represent the prevailing hydrodynamic forces, with coarse sand and gravel on the navigation channel, medium sand at the entrance and fine sand on the shelf. The diminishing of the sediment particle size towards the shelf, accompanies the reduction of the current velocity in the same direction (Dias et al., 2000, 2003; Almeida and Dubert, 2003). This grain-size gradient was effectively captured in the acoustic diversity pattern, resulting in a very close agreement between the spatial distribution of the acoustic classes and the sediment pattern. The four acoustic classes corresponded to the three major soft sediments (coarse, medium and fine) and the hard bottom. This acoustic approach may thus represent

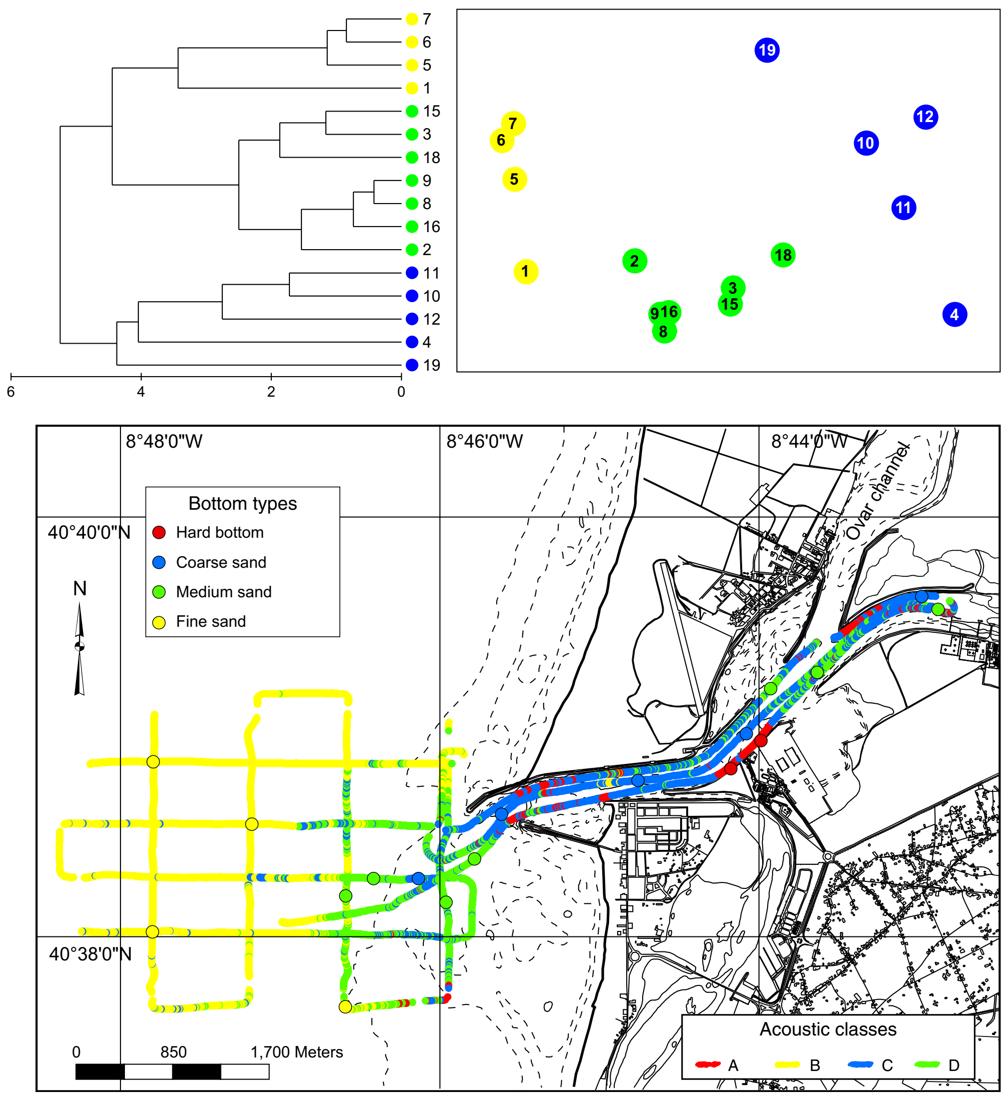

Fig. 4. Top – classification and ordination diagrams issued from the analysis of the sediment data presented in Table 4. Bottom – final acoustic diversity solution of the bar channel of Ria de Aveiro and near-shore shelf, with a GIS representation of the four acoustic classes jointly displayed with the bottom types.

a very valuable tool to study the sediment seascape, in areas where conventional sediment sampling using grabs or towing video is less favourable due to strong ebb and flow currents and frequent ship traffic.

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Validation of soft bottom benthic habitats identified by single-beam acoustics

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Abstract

Acoustic diversity charts were produced for a Portuguese soft bottom mid-shelf area, depth from 30 to 90 m, using a single-beam echo sounder coupled to the acoustic systems QTC VIEW™ Series IV and V. A similar acoustic pattern was identified by both systems, which, after ground-truth interpretation based in available sediment and biological data, established a preliminary spatial distribution model of the benthic habitats in this coastal area. However, some of the acoustic areas were interpreted using one or very few sediment and benthic samples. A specific validation survey was conducted a posteriori, in which the positioning of the sediment and benthic community sampling sites was based on the acoustic diversity previously identified. The results clearly confirm the benthic habitats distribution model suggested by the acoustic method, indicating a high potential for the use of such approach in the identification and mapping of large-scale soft bottom coastal shelf habitat diversity.

Keywords: Benthic habitats; Acoustic classification; Coastal shelf; Portugal

1. Introduction

Seabed habitats discrimination and mapping using single-beam acoustic methods is becoming more common, e.g. Hamilton et al. (1999), in Australia, Smith et al. (2001), in the USA, Anderson et al. (2002) in Canada, or Ellingsen et al. (2002), in Norway. These, as with most of the applications using acoustical methods for seabed mapping, tend to study areas characterised by a wide variety of bottom features. A successful example of habitat assessment from a relatively monotonous soft bottom area is given by Freitas et al. (2003a), in Portugal, for a near shore shelf area characterised by a range of grain-size sandy sediments all with very low silt content.

When compared to habitat mapping methods based on the point collection of sediment samples for the subsequent analysis of a suite of variables, acoustic methods have clear advantages. They allow a much finer spatial discrimination due to almost continuous echo sampling, and avoid the physical and biological disturbance associated with the removal of sediment samples. If the seabed targeted is heterogeneous as shown by different acoustic signatures, and the acoustic data, simultaneously collected with positioning data, is classified into acoustic classes that are then plotted in a geographic information environment, then the acoustic approach may produce an adequate method to identify and map seabed discontinuities. However, the use of acoustics for the identification of benthic habitats requires a valid, calibrated interpretation as a variety of factors may influence the echo, some of which are totally independent of the benthic habitats, namely the characteristics and baseline settings of the acoustic equipment (echo-sounder frequency and output power, transducer beam angle, receiver input gain). Ground-truth validation is thus of utmost importance in the process of assigning benthic habitats to acoustic classes.

In the coastal shelf off Lisbon, Freitas et al. (2003b), used the acoustic classification systems QTC VIEW™ Series IV and V, to discriminate the benthic habitats in an area where the sedimentary environment exhibited a smooth gradation from fine sands to mud with silt and clay content

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ranging, respectively, from below 5% to above 80% of total sediment dry weight. The available sediment and macrofaunal data have produced a preliminary spatial model for the distribution of the soft bottom benthic habitats for this coastal region, although some of the acoustic areas were interpreted using data from a single or very few sediment and macrofaunal samples. This paper indicates a specific validation exercise for the proposed spatial pattern, by increasing the number of ground-truth sediment and biological samples, positioned according to the acoustic diversity chart and checking their agreement to the spatial distribution model.

2. Material and methods

2.1. Field sampling

For the validation of the acoustic diversity pattern, sediment samples were taken at 60 sites in October 2002, using a 0.1 m^2 Smith–McIntyre grab. Two samples were collected per site, one for sediment and one for macrofaunal analysis. The latter was washed over a 1 mm-mesh screen and the remaining material fixed in 4% buffered formalin. Sites 1–20 were located as in Freitas et al. (2003b), and sites 21–60 were distributed in order to ensure a detailed coverage of the acoustic gradient previously identified. The positioning of the 60 sampling sites (Fig. 1) was superimposed on the acoustic survey grid used by Freitas et al. (2003b).

2.2. Laboratory analysis

Sediment grain-size was analysed by wet and dry sieving, following Quintino et al. (1989). The silt and clay fraction (particles with diameter below 0.063 mm) and the gravel fraction (particles with diameter above 2.000 mm) were expressed as a percentage of the total sediment, dry weight. The sand fraction (0.063–2.000 mm) was dry sieved

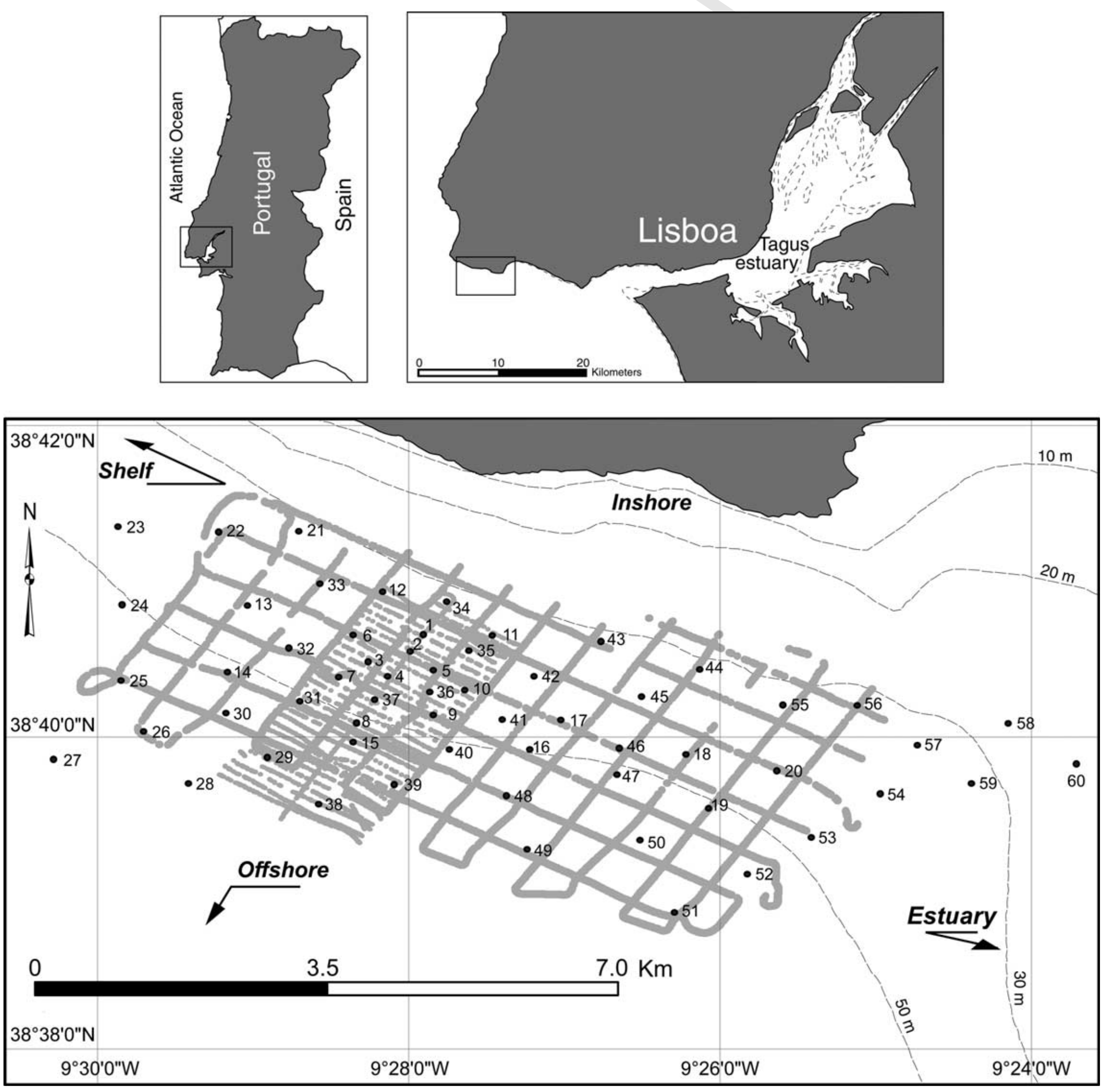

Fig. 1. Study area showing the location of the 60 sampling sites for sediment and macrofauna analysis, superimposed on the acoustic survey lines from Freitas et al. (2003b).

through a battery of sieves spaced at 1 phi (Φ) unit interval ($\Phi = -\log_2$ the particle diameter expressed in mm). The sediment was classified according to the median value (P_{50}), and the Wentworth scale (Buchanan, 1984). Total volatile solids were determined by loss on ignition at 450 °C (Byers et al., 1978). Redox potential was measured on board at −4 cm from the sediment surface with specific probes (Pearson and Stanley, 1979).

For the macrofauna analysis, the animals from each sample were sorted and identified to the highest possible taxonomic separation, and a sample/species/abundance matrix was produced.

2.3. Data analysis

The identification of the environmental and biological affinity groups used classification and ordination analysis, with PRIMER (Clarke and Gorley, 2001) and MVSP software (Kovach, 1999). The environmental data matrix consisted of 60 sites × 6 variables (gravel, sand, fines, median grain-size, total volatile solids and redox potential). A sites × sites resemblance matrix was produced using normalised euclidean distance and submitted to average clustering in order to identify the environmental affinity groups, which were represented on axes 1 and 2 of a principal components analysis.

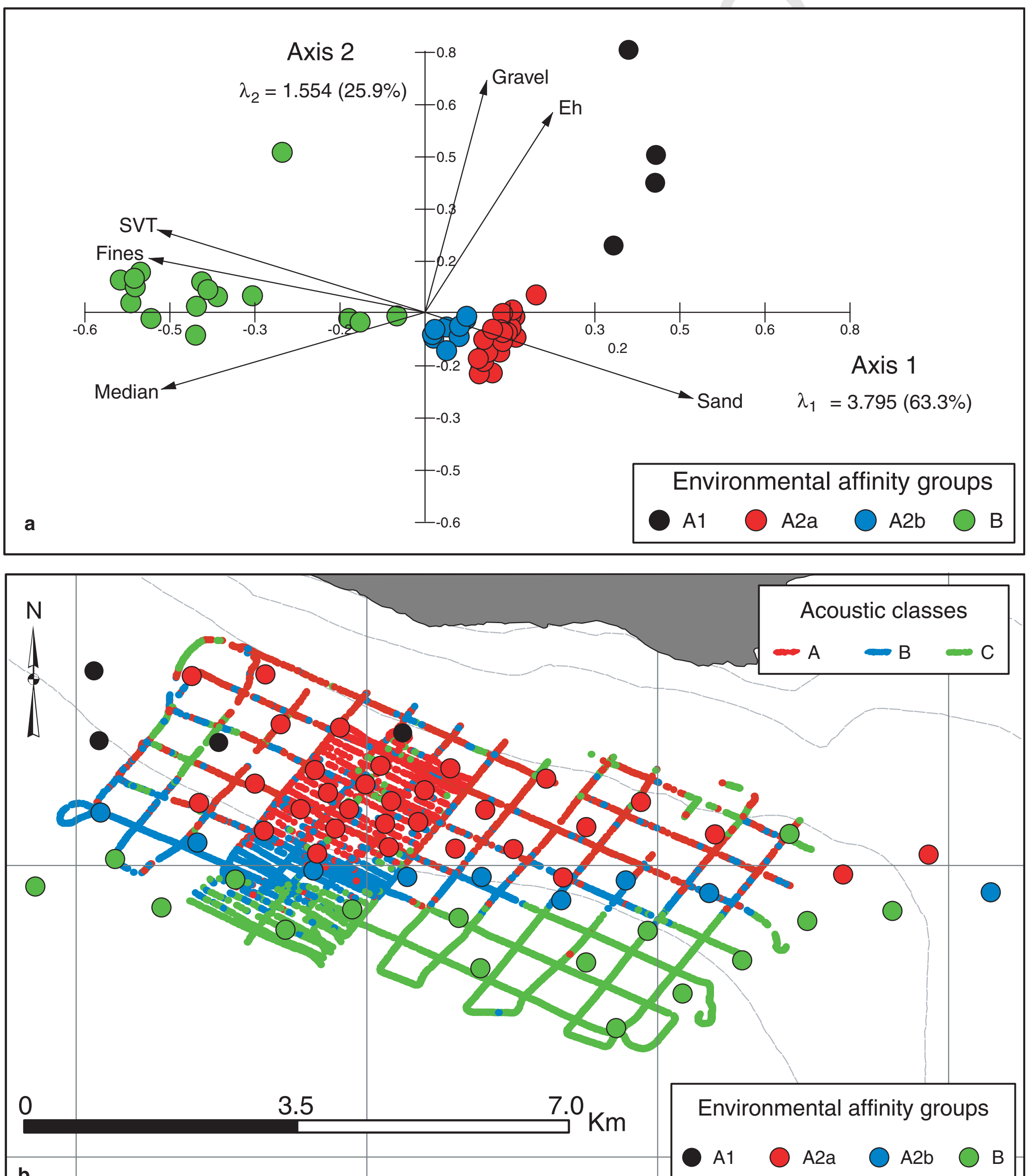

Fig. 2. Sedimentary affinity groups A1, A2a, A2b and B, identified by cluster analysis, (a) plotted on axes 1 and 2 of a principal components analysis and (b) superimposed over the acoustic classes by the use of a geographic information system (GIS).

The biological data were represented by a matrix of 60 sites × 236 species, described by their abundance per 0.1 m^2. Following a square root transformation, a [sites × sites] Bray–Curtis similarity matrix was produced and classified with the average clustering algorithm. The ordination of the affinity groups was represented on a correspondence analysis.

To verify the spatial consistency between the environmental, the biological and the acoustic gradient, the sedimentary and the biological affinity groups were overlaid on the acoustic diversity charts established in Freitas et al. (2003b), using a geographic information system (ArcGis).

3. Results and discussion

3.1. Sedimentary gradients

A principal components analysis of the environmental data (Fig. 2(a)) displays the affinity groups identified by average clustering, A1, A2a, A2b and B. A summarised characterisation of each group is given in Table 1. The coarser sediment with the highest redox potential values corresponds to group A1. Group A2a corresponds to fine sand with the silt and clay fraction below 5%. Very fine sand with the silt and clay fraction above 5% characterises group A2b. Finally, group B includes the sampling sites with the highest values for fines content, total volatile solids and the median grain-size, and the lowest values for the redox potential (cf. Table 1).

Fig. 2(b) represents the sedimentary affinity groups superimposed on the acoustic classes, by the use of a geographic information system. With a progression through the groups A1 → A2a → A2b → B, the superficial sediments show a gradual increase of the median grain-size value, fines and total volatile solids content. The majority of the study area corresponds to fine sand with low fines content (Group A2a, cf. Fig. 2(b) and Table 1). The fines proportion of the superficial sediments increases with increasing depth, along the inshore–offshore axis, and towards the estuary, along the shelf–estuary axis. Mud with high silt and clay content characterise the end part of this gradient (group B, cf. Fig. 2(b) and Table 1). The transition between the two major sediment groups, clean fine sand and mud is made through a relatively narrow area of very fine silty sand (group A2b, cf. Fig. 2(b) and Table 1).

3.2. Biological gradients

Axes 1 and 2 of a correspondence analysis of the biological data (Fig. 3(a)) displays the affinity groups identified in cluster analysis, A1, A2a, A2b and B. Table 2 shows the mean species richness and abundance for each group. The distribution of the biological groups in the correspondence analysis (cf. Fig. 3(a)) indicates a continuous change between the groups, which is confirmed by the species succession presented in Table 3. Although the analysis was conducted with the whole set of 236 species, Table 3, for reasons only related to the simplicity of representation, only includes a subset, which arguably best represent the whole group of species. This subset, comprising 26 species, was obtained using the PRIMER routine BVSTEP. With this routine, a subset of species was determined in order to produce a Bray–Curtis resemblance matrix with a Spearman correlation of 0.95 with the Bray–Curtis resemblance matrix obtained with the whole set of species. An initial subset of 12 species was found that matched the correlation threshold of 0.95. After removing this initial subset, a second subset of 14 species also attained this correlation value with the original data matrix. Once these 14 species were excluded, no further species subset was obtained which could match the requested correlation threshold. Together, the matrix with the selected 26 species presents a Spearman correlation of 0.977 with the original data matrix.

The spatial pattern represented by the biological affinity groups also follows the inshore–offshore and the shelf–estuary directions (Fig. 3(b)), as identified by the sedimentary groups. At the Northwest extremity, group A1 presents the highest species abundance and is dominated by small interstitial annelids (Table 3), in agreement with the fact that this region is constituted by loose coarse sand with low fines content (cf. Table 1). At the Southeast extremity,

Table 1
Data means with standard deviation (sd) for the sedimentary groups identified by cluster analysis

Sampling sites	Affinity groups							
	A1		A2a		A2b		B	
	13,23,24,34		1–12,14,17,21,22, 31–33,35–37, 41–46,55,57,58		15,16,18,20,25, 30,40,47,60		19,26–29,38, 39,48–54,56,59	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
Redox potential (mV)	337.3	77.47	49.7	66.07	60.3	33.04	35.4	69.92
Total volatile solids (%)	1.1	0.19	1.1	0.24	2.0	0.31	5.7	1.55
Fines (%)	0.4	0.29	3.3	1.29	11.4	2.42	67.4	22.88
Sand (%)	88.7	12.54	96.5	1.25	88.4	2.48	31.6	22.02
Gravel (%)	10.9	12.30	0.2	0.15	0.2	0.12	1.0	3.23
Median (ϕ)	0.7	0.32	2.7	0.11	3.2	0.12	>4.0	–
Sediment classification	Clean coarse sand		Clean fine sand		Silty very fine sand		Mud	

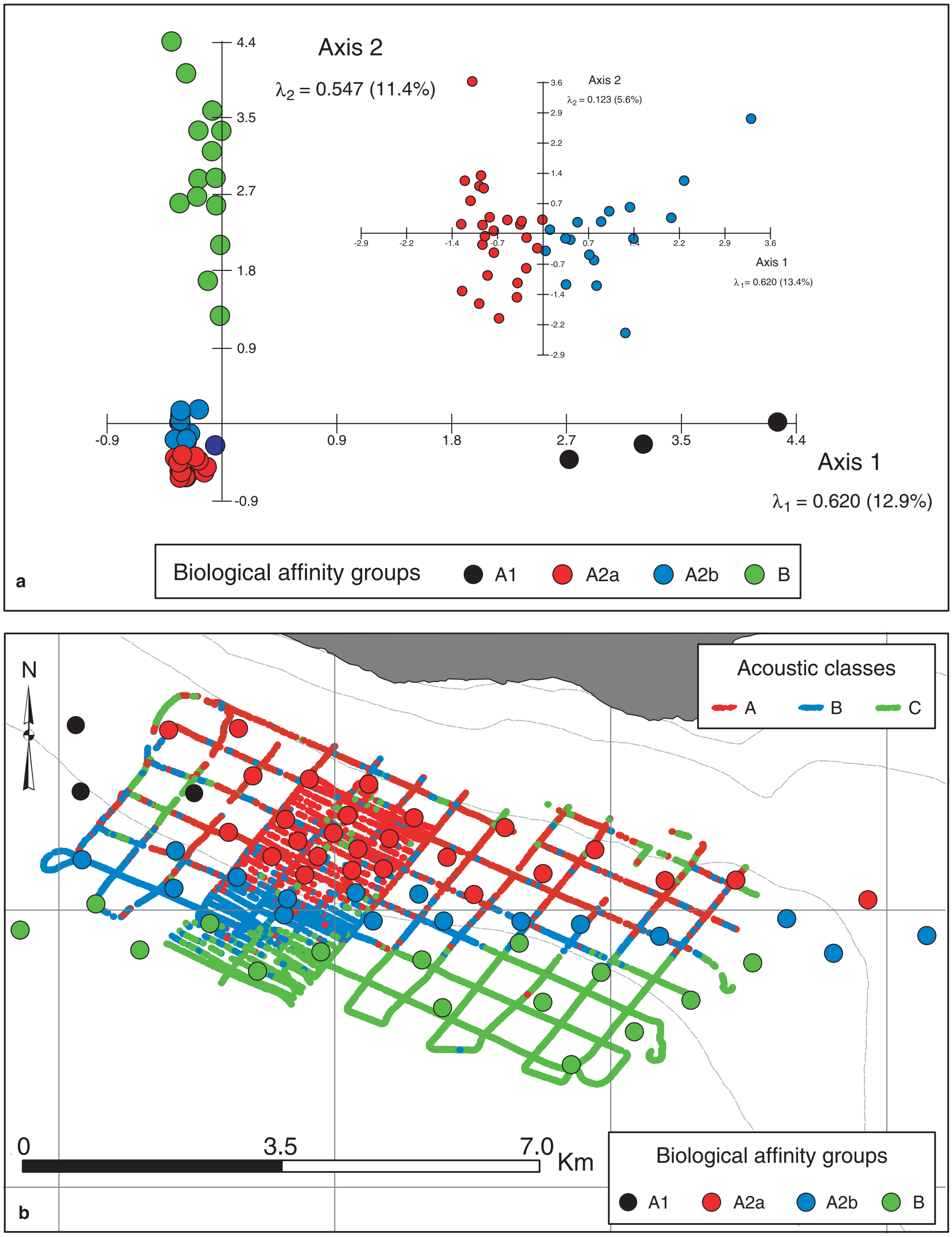

Fig. 3. Biological affinity groups A1, A2a, A2b and B, identified by cluster analysis, (a) plotted on axes 1 and 2 of a correspondence analysis, and (b) superimposed over the acoustic classes using GIS. The inset diagram in (a) details the ordination of sub-groups A2a and A2b, after deletion of the groups A1 and B.

group B is characterised by faunal impoverishment, both in species and numbers of specimens (cf. Tables 2 and 3), also in agreement with the high fines content of this region, and the overall higher sediment contamination of these muddy areas closer to the mouth of the Tagus Estuary, when compared to the inshore sandy sediments (Quintino et al., 2001). The groups A2a and A2b present the highest values of species richness and are characterised by a gradual succession of dominant species (cf. Tables 2 and 3). The two major benthic assemblages correspond to the affinity groups A2a and B (cf. Fig. 3(b)). The transition between these is made through a relative narrow belt, presenting the highest mean species richness (group A2b, cf. Fig. 3(b) and Table 2). This succession has a clear corre-

Table 2
Mean species richness (S) and mean abundance (A) per unit sample with the corresponding standard deviation (sd) for the biological groups identified by cluster analysis and confirmed by ordination analysis

Sampling sites	Affinity groups							
	A1		A2a		A2b		B	
	13,23,24		1–7,10–12,17, 21,22,32–37, 42–45,55,56,58		8,9,14–16,18, 20, 25,30,31,40,41, 46,57, 59,60		19,26–29,38, 39,47–54	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
A/0.1 m^2	529.3	420.02	223.0	68.75	288.6	131.33	52.5	36.95
S/0.1 m^2	37.0	8.19	41.4	8.48	48.6	10.79	20.7	8.18

Table 3
Species succession in the biological affinity groups

	Groups			
	A1	A2a	A2b	B
Polygordius appendiculatus	**103.67**			
Nematoda n.i.	**48.67**	0.04	0.56	
Paradoneis cf. lyra	**25.33**		0.06	2.27
Spio decoratus	**14.67**	8.08	4.94	0.07
Spiophanes bombyx	**11.00**	7.73	10.06	0.07
Tellina fabula		**24.23**	1.69	
Siphonoecetes kroyeranus	0.33	**5.19**	0.50	
Euspira nitida	1.33	**2.81**	1.63	
Chaetozone setosa	4.67	**25.50**	9.69	0.33
Magelona johnstoni	0.33	**14.58**	4.88	0.40
Nemertea n.i.	7.00	**7.38**	6.31	0.80
Ampelisca brevicornis		**8.38**	3.94	0.60
Lumbrinereis latreilli	1.00	1.46	**46.81**	10.73
Hyalinoecia bilineata	2.00	9.65	**30.88**	0.40
Glycera tridactyla	1.00	6.23	**7.06**	0.67
Abra alba	0.67	3.62	**13.31**	0.27
Magelona filiformis		3.92	**7.50**	
Thyasira flexuosa		0.08	**2.94**	1.33
Tellina compressa		0.58	**8.44**	1.80
Ampelisca sp.		8.69	**9.13**	1.13
Prionospio fallax		7.88	**12.81**	0.40
Notomastus latericeus		0.04	0.06	**2.00**
Poecilochaetus serpens			0.19	**0.53**
Paraprionospio pinnata			0.31	**1.20**
Heteromastus filiformis				**1.67**
Thyasira sp.				**2.33**

The taxa are represented by their mean abundance per unit sample (0.1 m^2) in each group and include the species subset that best represents the whole data matrix (see text). Highlighted values indicate the group where each species presents the highest mean abundance.

spondence in the sedimentary groups (cf. Figs. 2(b) and 3(b)).

3.3. Validation of benthic habitats

The sedimentary and the biological data both indicate four soft bottom benthic habitats for this coastal area, as gradients from inshore to offshore and shelf to estuary. Photographs from the superficial sediment layer of samples taken in each are shown in Fig. 4. To the Northwest part of the survey region, there is a relatively small area characterised by loose coarse clean sand (Fig. 4(a) and cf. Figs. 2(b) and 3(b)), whereas to the Southeast, there is a very large area where mud with very high silt and clay content dominates (Fig. 4(d) and cf. Figs. 2(b) and 3(b)). Between these two areas extends a large relatively homogeneous area of clean fine sand (Fig. 4(b) and cf. Figs. 2(b) and 3(b)) and a narrow belt of silty very fine sand, which supports the characteristic patches of the tubicolous polychaete *Hyalinoecia bilineata* (Fig. 4(c) and cf. Figs. 2(b) and 3(b)). The acoustic pattern identified and described in Freitas et al. (2003b) very closely matches the distribution of these habitats, which, as shown in Figs. 2(b) and 3(b), does not follows the overall depth gradient, thus indicating the independence of the acoustics from depth. The increase of the number of ground-truth sampling sites from the 20 available in a previous assessment (Freitas et al., 2003b), to 60 in the present study, clearly confirms the spatial model previously suggested by the acoustic method, which in some cases was sustained by a single or only very few sampling

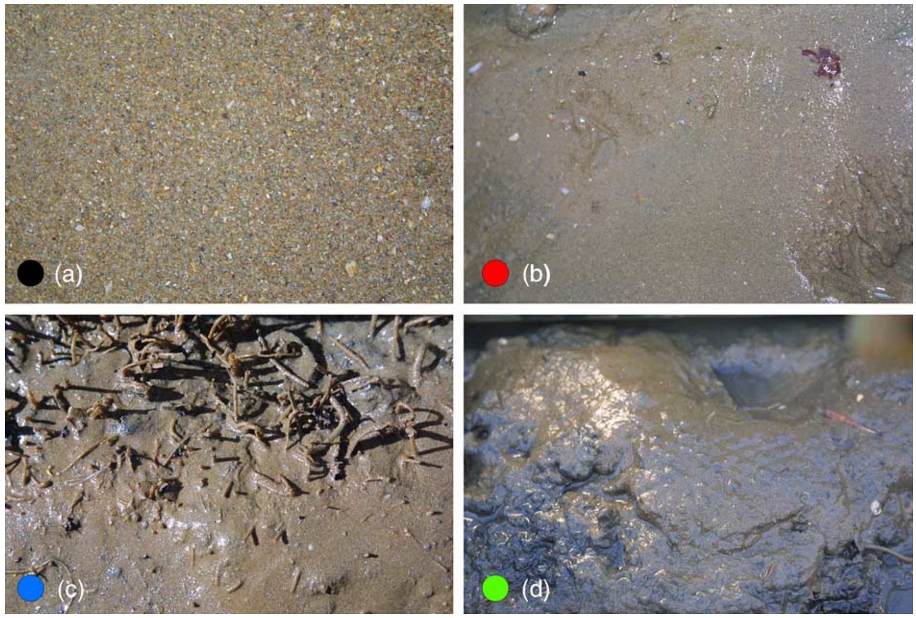

Fig. 4. Photographs of the superficial sediment layer in each benthic habitat: (a) loose coarse sands dominated by interstitial annelids, located towards the outer shelf; (b) fine sand with low silt content; (c) narrow belt of silty very fine sand, showing the characteristic patches of the tubicolous polychaete *Hyalinoecia bilineata*; (d) impoverished mud with very high silt content, located towards the entrance of the estuary. The colored circles correspond to the sedimentary and biological affinity groups represented in Figs. 2 and 3.

sites. This is the case of the large area located to the Southeast occupied by the mud habitat (acoustic class C in Fig. 2(b)), which in Freitas et al. (2003b) was supported by a single ground-truthed sample, and the narrow transition belt of silty very fine sand characterised by the tubicolous polychaete (acoustic class B in Fig. 2(b)), then supported by only three ground-truthed samples. The large extent of clean fine sand (acoustic class A in Fig. 2(b)) is also confirmed by a larger number of samples, although this habitat was already well represented by ground-truthed samples in Freitas et al. (2003b).

At the Northwest extremity, the present study confirms the presence of a coarser sand habitat, which in previous studies was also indicated by a single sample (Quintino et al., 2001;Freitas et al., 2003b). The fact that these coarser sediments, inhabited by a particular faunal assemblage, have no corresponding acoustic class is probably because the acoustic survey covered a small spatial extent and hence only a small number of echoes were obtained in such sediment type. This could have limited the ability of the acoustic classification software to establish a separate acoustic class. However, those areas are not classified as the surrounding acoustic class A, but appear classified as the acoustic class C, which corresponds to the mud habitat (cf. Fig. 2(b)). A similar situation was observed in other inshore survey areas, where also intrusions of the acoustic class C were noticed (cf. Fig. 2(b)). In these other cases, the intrusions of the acoustic class C did correspond to heterogeneous sediment identified by the ordination analysis and characterised by higher proportions of both the silt and clay and the gravel fractions. When compared to the clean fine sand and the silty very fine sand, these other sediments have one common characteristic: they are much less compact, allowing the grab sampler to penetrate deeper. Given that the acoustic survey was conducted with an echo sounder operating at 50 kH (Freitas et al., 2003b), this apparent mis-classification could also have resulted from the fact that these two types of quite different grain-size sediment should allow a deeper sound penetration than the more compact fine and very fine sand. Results from other surveys on the Portuguese Northern coastal shelf also suggested that the mis-classification of a particular site was due to sediment compactness (Freitas et al., 2003a). Both results indicate that future work should focus on this apparent sensitivity of the acoustic method to such sediment property (compactness), namely through the use of synoptic dual-frequency surveys, one of which would penetrate less the sediment.

Despite that particular mis-classification, these results indicate the high potential for the use of the QTCVIEW single-beam acoustic approach in the identification and mapping of large-scale habitat diversity along the coastal shelf, namely in areas covering broad sediment types such as this one. Overall, the present work validates, through the analysis of a large number of ground-truth samples for benthic community and superficial sediment properties, the benthic biotopes distribution pattern, previously identified in this area through an acoustic survey (Freitas et al., 2003b). On purpose, an excess of ground-truth samples were used in this study. The fact that the both approaches (acoustics and sediment point samples) gave very coherent distribution areas for the three major benthic biotopes, reassures the acoustic approach as a reliable method for the detailed identification and mapping of large-scale habitat diversity in the coastal shelf.

This whole survey used a post-processing approach, i.e. all acoustic analysis were performed after the survey. The same acoustic system may be used in real-time classification (QTCVIEW series IV only), through the comparison of acquired echoes with previous ones, used to produce a catalogue of different acoustic classes, each assigned to a given seabed type. In real-time classification, this comparison is made as the vessel moves along the survey lines. With this strategy, the acoustic approach may be used to search for a particular seafloor feature or biotopes without the need for further ground-truth validation, as long as the method furnishes reliable results. Such reliability was assured by the validation approach followed in this work. Real-time benthic biotope surveys using single-beam acoustics have many promising applications, but are still at a very early development stage and require future research.

4. Conclusions

Freitas et al. (2003b), using a combination of acoustic and traditional sediment survey techniques, suggested a soft bottom habitats spatial model for a mid-shelf area, based in the fact that the acoustic classes, the sedimentary and the biological affinity groups, all followed northwest–southeast and coastal–offshore directions. Available ground-truth data (April 2001), served as validation of this model. However, some of the acoustic classes were interpreted using a single or only a few sediment and biological samples. A specific validation survey was conducted a posteriori and a total of 60 sampling sites were positioned according to the acoustic gradient previously established. The results clearly confirm the soft bottom benthic habitats distribution model suggested by the acoustic method for this coastal region and indicate high potential to use the method in real-time surveys.

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